Evaluation of CERES-Wheat Model for Planting Dates, Nutrient Application and Irrigation Regimes under Changing Climate Scenarios of Pakistan

BY

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To

The Controller of Examinations,
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We, the supervisory Committee, certify that the contents and form of thesis submitted by **Mr. Muhammad Usman Bashir,** Regd. No. 2003-ag-1805 have been found satisfactory and recommend that it be processed for evaluation by the External Examiner(s) for the award of degree.

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2003-ag-1805

DEDICATION

This humble effort is
DEDICATED
To
My beloved
MOTHER
and affectionate
FATHER

So much of what
I have become is because of you
and I want you to know that I appreciate you
Thank you
and
Love you

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(MUHAMMAD USMAN BASHIR)

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ABSTRACT

CERES-Wheat model was used to study the simulations of development, growth and yield of wheat at different sowing dates, nitrogen rate and irrigation levels recorded at Agronomic Research Area, University of Agriculture, Faisalabad during 2010-11 and 2011-12. Experiment-I comprised of three levels of fertilizer (80, 120 and 160 kg N ha^{-1}) in main plot and six different levels of irrigation at critical stages in sub-plots (Irrigation at Tillering, Stem Elongation, Booting and Grain Formation; Irrigation at Stem Elongation, Booting and Grain Formation; Irrigation at Tillering, Stem Elongation and Grain Formation; Irrigation at Tillering, Stem Elongation and Booting; Irrigation at Tillering and Stem Elongation, and Irrigation at Stem Elongation and Booting). Experiment-II comprised of two sowing dates (15th November and 15th December) in main plots and four irrigation levels at different levels of potential soil moisture deficit (Full Irrigation, 45mm, 60mm and 75mm PSMD) in sub plots. Experiment was conducted in RCBD with split plot arrangement, having 20 cm row spacing, 125 kg ha^{-1} seed rate, Sahar-2006 test cultivar and replicated thrice. Results showed that Full irrigation and 120 kg nitrogen ha^{-1} produced maximum yield. Net profit and benefit cost ratio was maximum in Full irrigation and 160 kg nitrogen ha^{-1}. Irrigation at 45 mm PSMD sown at 15th November produced maximum grain yield. Climate change scenarios showed reduction in wheat yield from 8.45 to 14.55% and 19.03 to 22.55% in mid and end century. Adaptation strategy for climate change and water shortage by 20% for mid-century is 22nd November sowing date and 20% increase in seed rate.

Chapter 1 INTRODUCTION

Agriculture sector is backbone of Pakistan’s economy, contributing 21% to GDP, employing 45% of labour and 60% of rural population depends on it for their livelihood. It plays a vital role in ensuring food security, economic growth, reducing poverty and transforming towards industrialization (GOP, 2012).

The average water requirement during Kharif season is 65.9 million acre feet. The average annual water availability in Kharif season during last eight years (2004-05 to 2011-12) was 64.19 million acre feet and Pakistan is almost meeting its water requirement during Kharif season. Average water requirement during Rabi season is 36.4 million acre feet. But water available during the season was estimated to be 29.4 (21.35 % less than normal availability). Average annual water available in last Rabi season was 31.9 million acre feet indicating a shortfall of almost 4.5 million acre feet. So Pakistan is facing a severe shortage in Rabi season (GOP, 2012).

In Pakistan, Rabi season starts from October to December and ends from April to May. Crops cultivated in Rabi season are Wheat, gram, lentil, tobacco, rapeseed, barley and mustard. Wheat is the major and most important crop of the season, cultivated throughout the country ranging from arid to sub-humid climate, in both irrigated and rainfed conditions. It is staple food of Pakistan and chief source of protein. It was cultivated on an area of 8.6 million hectares (2.6% less than last year’s area), with a production of 23.5 million tons and average yield of 2714 kg ha^{-1} showing a negative growth rate of 4.2% (GOP, 2012).

Total area of Pakistan is 79.61 million hectare, out of which 22.75 million hectare area is under cultivation. Total irrigated area (18.67 million hectare) is comprised of 6.4 million hectare under canals, 3.92 million hectare under tube well, 7.60 million hectare under canal plus tube well and 0.75 million hectare under other sources of irrigation (wells, karez etc). Remaining 4.08 million hectare area (17.93 % of total cultivated area) is rainfed. Efficient irrigation system is a universal requirement for higher agricultural production by increasing cropping intensity. Pakistan has a good irrigation canal network. But we are wasting our resource due to lack of sufficient water reservoir capacity and improper lining of canal. There was a lot of variability in intensity and frequency of rainfall due to Climate change. Normal average rainfall during the monsoon season (July-

September) is 137.5 mm. In 2011-12, Pakistan received 236.5 mm rainfall (99% more than normal). During winter 2012 (January-March), rainfall received (34.2 mm) was 51.4% less than normal rainfall (70.5 mm) during the season, resulting in decrease in withdrawal of water from canal head (GOP, 2011). So decrease in canal water supplies and variability in rainfall are serious threats for agriculture.

Fertilizer is another most important and expensive input for crop production. Balanced fertilizer application can increase yield from 30 to 60% in different crops. One unit of fertilizer nutrient produces about 8 kg of cereals. Most of our soils are deficient in nitrogen. Intensively cultivated crops are depleting soil fertility. Domestic fertilizer production during fiscal year 2011-12 was 2255 thousand tons (1.4 % less than previous year). The reduction in domestic production was caused by curtailment of natural gas to fertilizer industry and some fertilizer plants produced less than their production capacity. To compensate the lower production, we imported 1024 thousand tons fertilizer (92.6% more than previous year). The prices of urea, DAP, CAN and NP also increased by 81.4, 38.8, 75.5 and 45.7 % respectively in July-March 2011-12 as compared to same period of last fiscal year (GOP, 2012). So there is a dire need to optimize the use of fertilizer for sustainable productivity.

Sowing date is another yield determinant factor. Delay in sowing of wheat results in decrease in yield due to exposure of plant to high temperature at later growth stages and reduction of growing season length. Plant exposure to high temperature also results in loss of tiller fertility. Late sowing of wheat results in lower grain weight. Early sown crop takes longer maturation time and early anthesis, and reduces plant exposure to high temperature during reproductive stage (Coventry *et al.*, 2011).

Abiotic stresses (drought, nutrient deficiency, salinity, heat, ozone depletion and UV radiation) pose negative impact on crop productivity and considered as a major constraint to global food security. In coming decades, these events might become more prevalent due to climate change (Wang and Frei, 2011). Under-developed countries of Asia, in tropics and sub-tropics, have increasing food demand, but these stress factors may cause risk of food shortage (Wassmann *et al.*, 2009a). Stress, imposed due to climate change, alter the physiological processes of plants by changing the rate of photosynthetic gas exchange and assimilate translocation (Morgan *et al.*, 2004), water uptake and evapotranspiration (Katerji *et al.*, 2010), nutrient uptake (Sanchez-Rodriguez *et al.*, 2010), antioxidant reactions (Apel and Hirt, 2004), programmed cell death (Kangasjärvi *et al*., 2005), and altered gene expression and enzyme activity (Frei *et al*., 2010b). If these processes occur over prolonged period, quantity and quality of crops is severely affected.

Climate change and global warming is observed worldwide. It affects various components of ecosystem and economy. Climate change has resulted in sea level rise (17 cm in last century), global temperature rise (ten warmest years occurred during last twelve years), warming ocean (0.302 ^oF since 1969) shrinking ice sheets (Greenland lost 150-250 km^3 ice per year and Antarctica lost 152 km^3 ice from 2002 to 2005), declining arctic sea ice, glacial retreat (Alps, Himalayas, Alaska) and ocean acidification (increased by 30% since green revolution, 2 billion tons per year CO_2 absorption by ocean) (VijayaVenkataRaman *et al*., 2012).

Recent changes in climate have a quantifiable effect on crop productivity. Variation in precipitation and temperature has resulted in 23-60% and 37-41% variability in yield respectively (Li *et al*., 2010). Temperature has a key role in development and formation of grain by controlling the rate and duration of grain filling. Due to late planting, higher temperature during reproductive stage caused a maximum reduction of 53.75% in grain yield. High heat intensity (0.538) lowered the grain yield (Riaz-ed-din *et al*., 2010). Ear photosynthesis has a sizeable contribution in grain yield of wheat ranging from 13-33% under normal conditions and 22-45% under source limitation i.e. drought, defoliation (Maydup *et al*., 2010). Under increased CO_2 concentration, ear has stimulation of net photosynthesis as compared to flag leaf (Wechsung *et al*., 2000). Ear contribution to grain filling is expected to increase under drought and increased CO_2 conditions (Maydup *et al*., 2010). In developing countries, demand for wheat will increase upto 60% by 2050 (Rosegrant and Agcaoili, 2010). On the other hand, wheat productivity is projected to decrease in developing countries (where 60% of all wheat is produced) by 20-30 % (Lobell *et al*., 2008; Rosegrant and Agcaoili, 2010). Decreasing irrigation water supplies will stagnate or decrease on-form productivity, decline soil fertility and shift pest paradyne.

There is a dire need of awareness of impacts of environmental stresses on crop growth and productivity and design adaptation strategies in crop production to such adverse conditions (Ortiz *et al*., 2008; Wassmann *et al*., 2009b). Strategy should be proposed to face the challenges of climate change by agronomic management, breeding of novel genotypes adapted to climatic stresses. Some projects of breeding has been started to develop new varieties of cereals adapted to heat (Pinto *et al*., 2010), drought (Araus *et al*., 2008; Fleury *et al*., 2010), salinity (Ren *et al*., 2005), and tropo- spheric ozone (Frei *et al*., 2008). We should focus on quantification of growth processes and their response to adverse climatic conditions and optimization of agronomic management practices under changed climate scenarios. Focus of most agronomic efforts should be mitigation of yield losses due to hazards of climatic extremes.

Crop growth Model is an advanced tool for analyzing precision farming dataset for optimizing the crop growth and productivity. It is an inexpensive and less time consuming alternative for deciding the best management options under different soil and climatic conditions (Singh *et al*., 2008). Daily crop growth is integrated based on the effect of soil, management, weather, genetics and pests and get insight into spatial yield variability (Thorp *et al*., 2008). This tool calculates day to day effect of climate on crop growth and its transformation into yield. CERES-Wheat is a model in DSSAT (Decision Support System for Agro-technology Transfer) used worldwide to study the effect of soil, weather and crop management options on crop productivity.

Following objectives were designed for this study to investigate the effect of management options on crop productivity and its behavior in changing climate scenario of Pakistan:

1) To explore PSMD (potential soil moisture deficit) as an alternative approach for scheduling irrigation for improved Water Use Efficiency and yield.
2) To test the performance of CERES-Wheat model in simulating the growth, development and yield of wheat under different planting dates, fertilizer levels and irrigation scheduling.
3) To project the effect of climate change on productivity using CERES-Wheat model.

Chapter 2 REVIEW OF LITERATURE

2.1 Effect of irrigation on wheat

Irrigation is an important input on which high crop productivity rely. A major bottleneck limiting sustainable development of agriculture is water deficit, determining the crop growth and development. Drought has long been a scourge of humanity and a factor in conflict and war. Our farmers are facing a serious challenge of maintaining agricultural productivity under drought stress environmental conditions. Agricultural water management should be integrated with other water management practices to sustain the system and prevent catastrophe (Bouwer, 2000). Otherwise we have to rely on non-conventional resources (desalinated or pre-treated water). Water availability in densely populated arid area is less than 1000 m^3/capita/year, indicating its scarcity (Rijsberman, 2006). In water scarce region, there is a dire need of innovative and sustainable research and technology (like on-farm water management and treated water use) to use water efficiently. Supplemental irrigation and deficit irrigation are the useful strategies for improved benefits of water management (Pereira *et al*., 2002).

A possible option to meet the challenge of drought is deficit irrigation. Deficit irrigation, deliberate under-irrigation, can be translated into the words of decreasing water use while minimizing its adverse effects on crop productivity (Zhang *et al*., 2004). To adopt this technique, the basic requirement is the response of the various stages of the crop to water deficit extent, its duration and the monetary gains. The benefit of deficit irrigation can be described from three factors: increased WUE, reduced irrigation cost and opportunity cost of water. Water saved from deficit irrigation can be used to irrigate the additional area to get more production and compensate the lower yield particularly in water limiting situation. Du *et al*. (2010) investigated water saving irrigation method, temporal (regular deficit) irrigation, in winter wheat in semi-arid and arid conditions for four years. They observed similar photosynthetic rate maintained due to alternate furrow irrigation but transpiration rate was reduced. In extremely arid conditions, feasible irrigation cycle is seven days. High irrigation frequency with less water amount is better for grain yield. Water deficit severity and timing should be scheduled keeping in view stress tolerance capacity of crop variety. Another study was carried out by Ali *et al*. (2007) with a focus on irrigation scheduling based on deficit irrigation on different growth stages of wheat and its effect crop productivity. Deficit irrigation affected yield attributes significantly. Full irrigation (no deficit) yielded higher as compared to other treatments. Grain yield was reduced in declining order with deficit irrigation at Crown Root Initiation, tillering, booting to heading and flowering to soft dough stage. Comparing stress with two deficit strategies, alternative irrigation at Crown Root Initiation and Booting-Heading stage performed better. They suggested that under limited water supply, irrigation should be scheduled first at Crown Root Initiation (CRI), then at heading-flowering and then at tillering stage. Fang *et al*., (2006) observed that photosynthetic matter produced after heading contributes approximately 70-80% in yield of winter wheat. Hussain *et al.* (2004) observed that maximum fraction interception of light (90%) was higher when maximum LAI was more than 5.0 in fully irrigated plot. This fraction of light decreased to 80% when maximum LAI value declined to 4-5 in drought treatments. This decrease in LAI is associated with water stress which has ultimately reduced the biomass production (Asif *et al.*, 2012).

Zhang *et al*. (2004) explored the effect of irrigation scheduling on yield and WUE of wheat by applying unfixed amount of irrigation water at sowing, jointing and anthesis stage. No irrigation throughout the growing season resulted in lowest dry matter accumulation at maturity. Highest TDM accumulation was observed when crop was irrigated at anthesis stage. Partitioning of dry matter to grain was maximum in irrigation at anthesis, then in irrigation at jointing and anthesis, then in irrigation at sowing, jointing and anthesis and least in no irrigation throughout the season. It was due to relatively high net photosynthesis rate and grain filling rate which resulted in increasing accumulation of TDM and its transformation rate into grain weight. Irrigation at anthesis resulted in grain yield of 8837 and 9040 kg ha^{-1} in 2007-08 and 2008-09 when 43.8 and 13.8 mm water was applied respectively, with highest irrigation and precipitation WUE. Similarly Li *et al.* (2005) performed experiment for three consecutive years to optimize irrigation scheduling for grain yield and WUE of wheat. They found that grain yield (7423 kg ha^{-1}) and Water Use Efficiency (1.645 kg m^{-3}) was maximum at Evapotranspiration rate of 509 and 382 mm respectively. Comparing no irrigation with irrigation at Raising, Jointing and Flowering, total SWU (soil water use) throughout the growing season in two meter soil profile ranged from 263.9 mm to 135.6 mm respectively. They advised to delay the irrigation after sowing, until or after jointing due to lack of water deficit signs. Root growth is enhanced by first irrigation after sowing resulting in water absorption from deeper soil layers. Depending upon water availability, second irrigation should be applied at flowering to avoid drought stress at milking. Under limited water resources, first irrigation should be delayed till booting. Growth period from jointing to flowering determines the numbers of grains per spike. Second irrigation is recommended at jointing to Flowering stage to get high yield. 6659, 6914 and 7384 kg ha^{-1} was the average yield during three consecutive years at treatment Irrigation at Jointing, Flowering and Milking during first two years and at Irrigation at Jointing and Flowering during third year. Similar was the study of Ram *et al*. (2013) for consecutive three years to test the performance of wheat in different irrigation schedules based on critical growth stages and found that with the increase in the number irrigations during the growing season, WUE decreases. Five number of irrigation is not a guarantee to higher yield. Sometimes, four irrigations may yield higher. Similarly Tariq *et al*. (2012) reported significant increase in biomass as irrigation number was increased from one to four while increasing irrigation number from four to five did not show any significant increase in biomass. Sarwar *et al*. (2010) quoted the decrease in wheat yield in drought stress plots as compared to fully irrigated plot due to significant reduction in yield components particularly thousand grain weight and productive tillers.

Zhang *et al*. (2006) studied the effect of regular deficit irrigation on crop performance and WUE for two consecutive years. They observed higher yield and yield components in in regular deficit irrigation as compared to no stress treatment. Grain yield productivity was increased by 16.6 to 25 % along with saving of 14 to 22.9% water with regular medium deficit irrigation treatment as compared to full irrigation treatment indicating the over application of irrigation water than the requirement. They recorded the optimum soil moisture content level of 50-60% of FWC at Booting, 65-70% of field water holding capicity (FWC) at both booting and heading and 50-60% of FWC at grain filling period. There was another study by Xue *et al*. (2003) to compare the rainfed, deficit and full irrigation system in wheat. In rainfed plots, lowest shoot dry weight was observed due to decreased availability of soil water from booting to grain filling stage. In deficit irrigation system, crop received irrigation only at vegetative stage accumulated more biomass as compared to plots received irrigation only at reproductive stage. Higher grain yield was recorded in full irrigation system and deficit irrigation treatment having water application at reproductive stage due to higher uptake of water as compared to rainfed crop. But Zhang *et al*. (2004) observed a tremendous decline in grain yield with severe soil water deficit treatment and no significant reduction in grain yield and WUE in light soil water deficit treatment as compared to no stress treatment. They concluded that evapotranspiration can be reduced up to some extant without significant reduction in grain yield. Guttieri *et al.* (2001) and Dalirie *et al.* (2010) noted the decrease in biomass due to terminal drought stress because it reduced LAI, lowered leaf number and hastened physiological maturity.

Higher ET in high soil moisture condition is not the surety of high yield. Higher values of yield, HI and WUE were obtained in plots having mild stress during seedling or early vegetative stage. Under limited water situation, WUE is linked linearly to HI. WUE can be improved by increasing HI (Kang *et al*., 2002). Liu *et al*. (2013) used the simple and easy method of irrigation scheduling based on pan evapotranspiration for four growing seasons. They found quadratic relationship between crop yield and ET. Crop response factor was relative to ET. Sun *et al*. (2006) studied the relationship between grain yield, amount of irrigation, WUE and ET. They suggested that 300 mm irrigation water is optimum to get maximum yield, with an ET value of 426 mm. With increasing ET, water requirement of crop has increased but grain yield went down with a definite decrease in WUE, particularly in case of excessive irrigation. Shehzad *et al*. (2012) reported maximum RUE for both grain yield and TDM at 50mm PSMD.

2.2 Effect of Fertilizer on wheat

Critical nitrogen curve, a plant based diagnostic tool, can be used to determine nitrogen demand of the crop (Chen and Zhu, 2013). Wang *et al*. (2013) investigated the long term effect of nitrogen fertilization on soil water balance and yield of wheat. They found a positive relationship of nitrogen fertilization with water storage during fallow period (19-22%), precipitation storage efficiency (19-22%), more uptake during growing season (21-25%) and higher evapo-transpiration rate (7-8%). They recorded an increase in wheat yield (upto 244%) and WUE (upto 220%) with the increase in fertilizer rate but the depletion of soil water was also high. But according to White (2013), nitrogen requirement vary from year to year and from field to field. By increasing N application, grain yield increases, at the same time grain nitrogen percentage decreases.

During nitrogen application, spatial variability, soil moisture and nutrients must be taken into account. By using variable application rate, nitrogen fertilizer and nitrous oxide emission can be reduced without compromising wheat yield (Basso *et al*., 2013). Hussain *et al*. (2002) investigated the effect of different levels of fertilizer on wheat productivity in semi-arid agro-ecological zone of Pakistan. They recorded the significant effect of different levels of fertilizer on plant height, productive tillers, mean grain weight and harvested yield. Proper nutrition availability increases plant height (92 vs 85 cm), productive tillers (281 vs 262 m^{-2}), thousand grain weight (47.5 44.3 g) and grain yield (4.9 vs 4.2 t ha^{-1}). According to Hussain *et al.* (2006) maximum fertilizer level (200 kg ha^{-1}) produced maximum height (82 cm), productive tillers (351 m^{-2}) and grain yield (5 t ha^{-1}) as compared to low fertilizer level. Rehman *et al.* (2010) reported that increasing fertilizer from control delay the leaf senescence, sustain the leaf photosynthesis and extend the leaf area duration which results in higher leaf area index. Bavec *et al.* (2007) supported the idea with their finding that leaf area index varied from 1.0 to 6.5 for control to different nitrogen treatments.

Use of Leaf Color Chart (LCC) is also reported in literature to manage the nitrogen application with crop requirement (Shukla *et al.*, 2004). Iqbal *et al.* (2005) studied the effect of two fertilizer levels on wheat yield under rainfed condition. Both fertilizer level yielded statistically same in all three locations. So proper soil moisture availability is prerequisite for nitrogen availability to crop.

2.3 Effect of Sowing Date on wheat

The main objective of the crop production is to apply the input to an optimum level where output gives maximum economic return without degrading the resources. Optimum sowing time, being a basic principle of agriculture, has direct effect on crop productivity by influencing the growing season length and radiation use efficiency, especially in photo-thermal sensitive crops. Spink *et al.* (2000) investigated the effect of planting time (late September, mid-October and mid-November) on TDM accumulation and yield response of wheat to planting density for three consecutive years. They observed that each sowing date has a different optimum plant density level and optimum plant density increases with the delay in sowing time. Sacks *et al.* (2010) studied the global planting date pattern for wheat. They documented the plantation of spring wheat in cooler temperature (8-14 ^{o}C) in temperate regions. In Northern mid-latituds, spetember October is the general planting time for winter wheat.

Bannayan *et al.* (2013) concluded that planting crop during favorable temperature and optimum soil moisture will enhance crop productivity. Different techniques (like ET, number of drought days, number of drought days during growing season length etc) can be used as a base for optimizing planting date. There is a strong opinion that adaptive changes in sowing date may lead to increase in grain yield (Sommer *et al.*, 2013). Gul *et al.* (2013) and Akram (2011) documented higher crop growth rate in early and timely sown crop and growth rate was decreased with the delay in sowing.

Tahir *et al.* (2009) studied the effect of different sowing dates (early, mid and late December) on yield of wheat. They found that early December is optimum sowing time for wheat to attain maximum yield (4.2 t ha^{-1}). Delay in sowing reduces the yield upto 50 % in semi-arid region. The reason for decrease in yield with delayed sowing is the terminal higher temperature that shortens grain growing season and ultimately the growing season length (-28%). With delayed sowing till January, 65% yield reduction is also reported. Crop exposed to high temperature, due to late planting, start head emergence earlier (107 vs 72 days) as compared to wheat sown earlier. Reduced growing season length is the cause to low TDM accumulation and its transformation into economical part (Shah *et al.*, 2006).

Wajid *et al.* (2004) recorded the difference in grain yield of wheat in early (10 Nov) and late sowing date (10 Dec) by 60.6%. This higher yield is attributed to the higher number of productive tillers and mean grain weight. Similar was the trend for plant height (Ahmad *et al.,* 2005). Wajid *et al.* (2004b) reported that with early sowing, crop attained a higher leaf area in start days of growth but in the case of late sowing, lag period was increased due to low temperature and crop took more time to attain higher leaf area index. Due to the longer lag period, TDM accumulation was slow in late sowing. During march and onward, higher temperature boosted the crop dry matter accumulation but shortened the growing season length, which ultimately resulted in lower final TDM in late sowing as compared to early sowing (1228 vs 1370 g m^{-2}). Early sown wheat intercepted 25.7% and 19.8 % more light (372 vs 296, 503 vs 420 MJ) in 1998-99 and 1999-2000 respectively. Qasim *et al.* (2008); Anwar *et al.* (2011) and Inamullah *et al.* (2007) also documented that mid-November sowing date supported higher productive tillers, grains per spike, thousand grain weight and ultimately grain yield as compared to late sowing on 15th December due to reduced growing degree days, longer photoperiod and higher temperature during reproductive phase (Slafer and Whitechirch, 2001).

Qasim *et al.* (2008) compared the performance of growth and productivity of wheat in normal sowing date (mid Nov) and late sowing date (mid Dec). From Nov to

Feb, temperature was normal but in Mar, it raises upto 35°C with heat shocks. Delayed sowing significantly affected development of organs and transfer of assimilates from source to sink which is reflected in the form of shortening of plant height, days to anthesis and maturity grain, filling duration and ultimately in reduction of yield.

2.4 Water Use Efficiency

Water use efficiency can be defined as the amount of yield produced by using a unit of water at unit area. Water resources in agriculture are dwindling and there is a dire need to utilize them efficiently and increase crop water productivity. Need of the day is maximization of the water use efficiency without compromising the yield potential of our produce to sustain our productivity and meet the food security challenges particularly in scenario of rainfall variability and drought (Li *et al.,* 2005).

In deficit irrigation (conditioning less number and/or low quantity of irrigation), evapotranspiration is reduced and crop growth stage, most sensitive to drought, is identified to increase crop productivity. In temporal and spatial deficit irrigation, water use efficiency was found to be increased because alternate furrow irrigation reduced transpiration rate but maintained similar photosynthetic rate. In extremely arid conditions, low intensity and high frequency irrigation is better to increase water use efficiency. Regulated deficit irrigation and partial root zone irrigation maintains economic yield and improves WUE of cereals (Du *et al*., 2010).

Deficit irrigation strategy influences water productivity (WP) and irrigation water productivity (IWP). Water productivity is effectively boosted by deficit irrigation. Strategy of two alternate deficit irrigations (irrigation at CRI and Booting-Heading) yielded highest Irrigation Water Productivity, indicating the most efficient use of irrigation water. At high level of productivity, larger amount of water is required for incremental yield, indicating a decline in irrigation water productivity as yield increases above a certain level (Ali *et al*., 2007). Another two year study was planned to investigate the effect of irrigation scheduling based on irrigation at different growth stages (sowing, jointing and anthesis) on yield and WUE of wheat. Water use efficiency was maximum in treatment having no irrigation throughout the growing season, although grain yield was lowest. With the increase in amount of water applied, irrigation water use efficiency, precipitation use efficiency and irrigation benefit decreased in following order (Irrigation at Anthesis > Irrigation at Jointing and Anthesis > Irrigation at Sowing, Jointing and Anthesis) with both growing season (Zhang *et al*., 2006).

Kang *et al*. (2002) conducted experiments on irrigated winter wheat and compared the values of water use efficiency for different irrigation schedule. They observed that with decreasing the number of irrigation at different stages, although grain yield is decreased but water use efficiency is increased (i.e. one irrigation throughout the growing season). Surprisingly, WUE for two irrigation treatments was higher as compared to control. Results indicated that there is a possibility to optimize WUE without compromising high yield by refining irrigation schedules. Zhang *et al*. (2004) also investigated the relationship of grain yield and harvest index with water use efficiency (WUE) and water supply use efficiency (WsUE) through linear and non-linear regression models. They concluded that the maximum grain yield and harvest index (HI) is associated with maximum water supply use efficiency (WsUE) and but not with the highest water use efficiency (WUE).

Ali *et al*. (2007) observed that deficit irrigation significantly boosted WUE. Highest irrigation water productivity was obtained with irrigation application at tillering and booting stage. While comparing single water deficit strategies, stress at grain formation yield maximum WUE as compared to stress at Tillering, Jointing and Booting stages. While comparing single irrigation at crown root initiation with full irrigation, on an average, 68% water was saved with 19% reduction in yield. While comparing two alternate deficit strategies, 39% water was saved with 16% reduction in yield with irrigation at crown root initiation and booting stage as compared to well irrigated plot. So it is our choice to select a yield level with a recorded water saving. In another study, Xue *et al*. (2006) recorded a significant increase in grain yield and water use efficiency in deficit irrigation between jointing and anthesis as compared to rainfed. Increase in harvest index contributed to increase in WUE in deficit irrigation treatment. In deficit irrigation, time of irrigation is very important for increasing yield and water use efficiency, which they found to be irrigation at jointing and anthesis having maximum water use efficiency although grain yield is reduced by 16%. Khan *et al*. (2007) reported maximum WUE when irrigation was applied at the interval of 5 weeks. Increasing irrigation frequency decreased the WUE. Sun *et al*. (2006) also documented increase in WUE with increase in irrigation from zero to full. WUE in fully irrigated plot is higher as compared to plot in which irrigation is withheld at any critical growth stage (Wajid *et al*., 2006)

Simulation results of Jalota *et al.* (2006) showed that reducing irrigation below optimum level has reduced wheat yield and evapotranspiration, ultimately crop water productivity to a varying magnitude. Crop water productivity is reduced by 8 to 55%, depending on soil type, by reducing post-sowing irrigation water from 300mm to 75mm. Growth stage, most sensitive to water stress, was found to be grain development. Fereres and Soriano (2006) stated that deficit irrigation regime can be used to optimize water productivity when there is no possibility of full irrigation to crop. It increases not only water productivity but also profit of the farmer.

2.5 Crop Modeling

Experiments are the true outcome of response of an input in the form of productivity. But the results will be specific to site and year (White *et al*., 2002). There is a need of a tool that can extrapolate results beyond site, climate and management options particularly when trying to quantify the effect of irrigation scheduling on regional and local soil and climatic conditions and for spatial and temporal scale in a different year (Hartkamp *et al*., 1999). In this context, crop growth model have proven useful. Crop growth model is the numerical integration of growth processes along with its constituent processes with the aid of computer. To examine the crop yield productivity in response to climatic variation, models are classified in to broad classes i.e. Crop Simulation Models and Economic Models. Dynamic relationship between biophysical processes (photosynthesis, transpiration, moisture flow and nutrients), growth, management practices, climate and soil is the basis in crop simulation models (Rosenzweig and Iglesias, 1998). A model, once validated, becomes a standard tool to interpret the result of experiment (White *et al*., 2002). These models can be used for yield gap analysis and adaptive management practiced for different climate impact assessment studies. Output generated from these simulation models can be used as input in economic models (Antle *et al*., 2005).

Savage (2013) stated that farmers would benefit from long range weather forecasting models. Multi-model yield projection is a more reliable option for simulating the response of crop to different climatic conditions (Carter, 2013). Now-a-days, researchers are switching towards more rigorous multi-model ensembles to estimate the production of food in warmer world. Asseng *et al*. (2013) used 28 different growth and economical models for future forecast and studied the variability in their simulation. Cropping system models, in uncertain situation of water availability, can be used for rapid assessment of alternatives to on-farm water management (Thorp *et al.*, 2010). These models are process based computer simulation models. These can be used to simulate the plant growth and nutrient and water uptake processes during the growing season. The models take into account the weather conditions, soil and cultivar characteristics and management options to simulate growth, development and yield (Jones *et al*., 2003).

CSM-CERES-Wheat (Crop Estimation through Resource and Environment Synthesis, CERES) is an important simulation model used in decision support system and available as a part of DSSAT (Decision Support System for Agro-technology Transfer) which incorporate models of more than 25 different crops (Hoogenboom *et al.*, 2003; Jones *et al.*, 2003). Previous study has documented the the performance of CERES-Wheat in terms of yield (Panda *et al.*, 2003) and soil moisture (Eitzinger *et al.*, 2004) under water stress conditions. Lobell and Field (2007) used the crop growth simulation models to measure the effects of growing season temperature and rainfall on productivity of wheat and they noticed that the 30% or more variation in year to year yield is contributed by these two factors. Lobels and Monasterio (2006) calibrated CERES-Wheat model for different irrigation schedule and cited that yield loss in reduced irrigation schedule depends on the rainfall during the growing season. Model takes the soil and climate variability into account and output varies for different soil and climate. He *et al*. (2013) used CERES-Wheat model (v 4.5) to simulate the productivity of wheat in different irrigation schedule.

Researcher from all over the world are using CERES-Wheat for water and nutrient management i.e., in Egypt, for water stress and planting time management (Ouda *et al.*, 2005), in UK, for seasonal yield prediction (Bannayan *et al.*, 2003), in New Zealand, for water stress management (Jamieson *et al.*, 1998), in USA, for wheat yield improvement and irrigation management (Lobell and Ortiz-Monasterio, 2006; Barnes *et al.*, 2000), in India, for yield prediction (Hundal and Prabhjyot-Kaur,1997), in Spain, for spatial analysis of impacts of climate change (Iglesias *et al.*, 2000), in China, for varietal comparison (Rosenzweig *et al.*, 1999) and many more.

2.6 Climate Change

Climate change is the change in long term average of meteorological components. Three indicators of climate change are elevated CO_2 concentration, rise in global average temperature and rainfall variability. Rising concentration CO_2 (a greenhouse gas) has resulted in global warming (rise in global average temperature). Global warming is the cause of rainfall variability (change in intensity and frequency of rainfall distribution) which resulted in drought at one part of earth and floods, at the same time, in other part of world. Global warming is the root cause for melting ice on glaciers (which are retreating at very high rate) resulting in floods, sea level rise and inundation of coastal areas of world. Climate change due to social and ecological disruptions can be determined by observing its shift beyond historical analogues. Historical weather data of last forty five years was used as base temperature. It was concluded that tropics and developing countries will face the unprecedented climates first, showing their high vulnerability and limited capability to face the hazards of climate change.

Climate change is a threat to agriculture productivity shrinking food production potential and declining food availability. It is likely to affect developing world regions by 9-21% by 2050 (Ericksen *et al*., 2010; Easterling *et al*., 2007; Cline, 2007). It will result in change in average temperature and intensity and pattern of rainfall distribution having positive or negative effect on yield and production cost depending on the location (Misselhorn *et al*., 2012).

According to IPCC (2013) annual report, there is a declining trend in inter-decadal rainfall variability with more frequent deficit monsoon. Model simulated rise in temperature in winter with enhanced warming during night. Number of hot days and nights in summer is projected to increase. Since 1960 to 2010, global mean surface temperature has risen by 0.6 ^{0}C. Brohan *et al*. (2006) has confirmed these in a recent study, declaring the 20th Century as a warmest century. The warmest decade of the millennium was 1990s and ten of the eleven warmest years occurred between 1996 to 2005. Joshi *et al*. (2011) focused on the climate change indicators "when might something happen". Timing and extent of any threshold is very important to simulate its impact on crop productivity. They simulated that in higher CO_2 emission scenarios, global average temperature is projected to rise by 2^{o}C by 2060, but in lower CO_2 emission scenario, the same rise in temperature is delayed by several decades. Regionally, over large parts of Eurasia, Canada and North Africa, 2^{o}C threshold is projected to increase by 2040, if emissions continue to increase.

Howells *et al*. (2013) stated that the manners and extent of exploitation of precious resources (water, land and energy etc) contributes to climate change. For adaptation and mitigation, efficient and integrated resource management is necessary i.e.

CLEWs (Climate, land use, energy and water strategies). Climate change will have direct impact on water availability, its extent depending upon the geographic location, demographic changes, conditions of water availability and utilization, existing management and allocation system. According to IPCC (Inter-Governmental Panel on Climate Change) fresh water resources are highly vulnerable to climate change, posing serious threats to economic, social and ecological systems (IPCC, 2008; IPCC, 2012). It is projected that in some parts of the world, there will be severe drought due to decreasing trend in precipitation. At the same time, same parts of world will face severe flood and other extreme events like cyclones due to high intensity and duration of precipitation. Melting glaciers will result in increased water supplies and increased risk of sea-level rise. Soil and underground water quality will be compromised due to saltwater intrusion from rising sea level leading to global malnutrition by upto 25% by 2080 (Fischer *et al*., 2002).

In some regions, agricultural productivity is seriously impaired by prolonged dry spells and more intensified heat waves by causing moisture or thermal stress. In South Asia, dry land areas of arid and semi-arid regions are highly vulnerable to climate change. Water shortage has already reached its tolerance limits (CGIAR, 2004-05). Heat waves and water shortage has accelerated land degradation and threatened food security. The frequency of extreme hot days is projected to increase resulting in increase in global average temperature. Hussain and Mudassar (2007) observed that increased temperature results in decreased growing season length (GSL). Normally wheat requires 157 days to mature in hilly area of Pakistan. By using old historical average weather data (1976-2000), they calculated the required growing degree days to be completed in in Swat (156 days) and Chitral (156 days) districts. With the increase in 1.5 ^{0}C and 3 ^{0}C temperature, wheat yield is simulated to decrease by 7% and 24% respectively in Swat District and increase by 14% and 23% in Chitral District. 15% variability in rainfall has negligible effect on wheat yield. They suggested the testing of high yielding varieties of warmer areas in mountain areas for its survival. In the abundance of water in hilly areas, low temperature is the only constrain in high productivity.

Power *et al*. (2013) observed that severe weather and variability in rainfall is substantially driven by ENSO (El-Nino Southern Oscillation), affecting crop production, ecosystem and disease severity. They have shown the variability in precipitation and surface temperature due to projected changes in spatial pattern of ENSO. Two climate models have also confirmed these changes by using different scenarios of carbon dioxide

(Taylor *et al.* 2012; Moss *et al.* 2010; VanVuuren *et al.* 2011; Nakicenovic *et al.* 2000). By mid to late 21st century, there is a projection of drying in western Pacific Ocean and at the same time, heavy rain in central and western Pacific Ocean, caused by AL-Nino. During the El-Nino years, changes in precipitation anomalies can be correlated non-linearly with global warming by using Global Circulation Model.

Lobel *et al.* (2008) observed that the effect of climate change in some regions of world will be highly drastic as compared to others. Climate change scenarios generated by 20 different GCM (Global Circulation Model) were studied, by using statistical crop models, to identify adaptation priorities for crops in twelve food insecure regions of the world. They analyzed that South Asia and Southern Africa will highly suffer from climate change and investments in framing and executing adaptation strategies for climate change in these highly vulnerable areas would inevitably favor more as compared to other regions. Uncertainties vary for different crops and priorities for investment depend on altitude of risk. Coumou and Rahmstorf (2012) reviewed the intensity of recent extreme events (heat waves and precipitation extreme) and ostensibly found a link between these events and the influence of human on climate.

High temperature during grain filling in wheat is a major limitation to grain yield. Mondal *et al.* (2013) used high temperature resistant, early maturing lines in two different environment (Irrigated temperate with terminal heat stress and irrigated warm tropical). Wheat in temperate irrigatred environment had more number of days to heading (83 vs 68 days), higher grain yield (5.26 vs 3.63 t ha^{-1}) and thousand kernel weight (41.8 vs 37.4 g). Early heading varieties performed better than late maturing variety in both environments.

Gourdji *et al.* (2012) used wheat trial data of 25 years in 26 countries from CIMMYT (International Maize and Wheat Improvement Center) and simulated the wheat response to environmental variation by using empirical model. They observed that wheat is highly sensitive to warming particularly during grain filling stage. But sites having high VPD posed less negative impact of high temperature on wheat yield during this period. Lobell *et al.* (2011) studied temperature trend from 1980 to 2008 for growing season of many countries. Historic year to year variability in temperature exceeds by standard deviation value of one. Models, linking the yield to weather, indicate a decline in wheat yield by 5.5%. Temperature and precipitation variability has resulted in decline in wheat yield by 4.9 and 0.6% but CO2 concentration rise has boosted wheat yield by 3%. Overall impact of these three climatic factors was negative on wheat yield (-2.5%). Wheeler (2012) reviewed that extreme heat can reduce crop yield by accelerating wheat aging.

Global warming may pose greater threat to wheat productivity as compared to current model prediction. Lobel and Gourdji (2011) have observed that air temperature is increasing from last several decades. Average increase in minimum and maximum temperature is found to be 0.3 and 0.2 ^{o}C per decade respectively. Large range for increase in maximum temperature as compared to minimum temperature is due to greater impact of changes in radiation and cloudiness on day time as compared to night time (Lobell *et al*., 2007). Sommer *et al*. (2013) simulated the performance of wheat at 18 different sights in future scenarios by using old historical data in crop growth model. They found that the increase in temperature due to global warming has positive effect on growth and biomass accumulation on most of the sites. The effect of moderate projected increase in precipitation on yield was insignificant, particularly in rainfed areas due to higher evaporative demand. In elevated CO_2 scenarios, transpiration use efficiency was improved and water requirement did not increase. Due to climate change, hotter temperature during flowering increased flower sterility and reduced grain yield. Adaptive changes to sowing date may lead to increase in yield.

CO_2, an important factor for global warming, started rapidly increasing (2 ppm per year) in 2000s (Peters *et al*., 2011). Global average concentration of CO_2 in 2010 (390 ppm) was 39% higher as compared to that at the start of industrial revolution (278 ppm in 1750). From 1950 to 1980, globally solar dimming was observed (Wild, 2012). After that, global trends were more neutral with continued brightening in some areas (e.g. Europe, N. America) and continued dimming in some areas (e.g. East Asia, India). Elevated CO_2 concentration, being a carbon fertilizer to the plant, increase crop yield but on the same time it lowers protein contents (McGrath and Lobell, 2013). This change in quality of product may be due to reduced transpiration (reducing nutrient uptake due to reduced mass flow) and/or change in enzyme concentration. Change in physiological activity can be simulated under future climate scenarios. Pongratz *et al*. (2012) conducted experiments and simulated that high CO_2, in a geo-engineered environment, increases crop yield, because temperature effect is diminished and CO_2 fertilization effect retained. Wang *et al*. (2013) simulated that the increase in CO_2 concentration (450-800 ppm) elevated wheat yield (24%) due to increase in photosynthesis rate (33%) despite of reduction in stomatal conductance (-23%).

The evidences of climate change are mounting and demonstrate the need of adaptation measures to meet the challenge of food security (Challinor, 2011). Challinor *et al*. (2010) used crop growth simulation models and indicated that climate change, particularly increasing extremes of water and heat stress is increasing the threat of crop failure rate. Socio-economic measures (great investment) and/or biophysical measures (heat or drought tolerance in crops) are the possible adaptation strategies which become necessitated with the increase in mean temperature and associated extreme events.

Grain filling and yield is limited by onset of senescence. Lobell *et al.* (2012) measured the wheat growth via satellite for nine years and monitored the rate of wheat senescence at 34 ºC or higher temperature. They recorded that senescence rate was accelerated significantly at extreme heat. They concluded that global warming is a great challenge to wheat productivity and effectiveness of adaptation measures will depend on reduction in crop sensitivity to very hot days. Iizumi *et al.* (2013) assessed the reliability of hind-casts of failure of crops by linking seasonal climatic forecast with statistical crop models. They found that yield loss is reliably predictable if climatic forecast is near perfect. Wheat production can be reliably predicted by using within season hindcast, at just three months before final harvest. Variation in reliability in estimates depends on the crop sensitivity to climate and production technology used. They recommended seasonal climatic forecasts to predict crop failure and develop adaptation to climatic extremes.

Information of only climate is not sufficient for anticipating and reducing the impacts of climate change. Study of vulnerability is also required to anticipate the effective resilience of society to such disruptive events of climate change (Stern *et al.*, 2013). Arnell *et al.* (2013) presented the magnitude and uncertainty, at global scale, in climate change impacts. The impacts of climate change forecasted at global scale are robust although the spatial pattern of climate change is uncertainty.

Crop Production and food security is threatened by climate change. Negative effect of climate change on crop production may be turned into gains by planned adaptation (Challinor *et al.*, 2009). Inspite of simplistic approach, we should use comprehensive approach, keeping in view all key factors that affect yield, to get more reliable output otherwise results may be misleading (Semenov *et al*., 2012). Multi-model uncertainty analysis is another option to check the variability and get more accurate outputs (Asseng *et al*., 2013). Effective government policies (like price support) and strong management decisions (like multiple cropping system) can make farmers stronger than effects of climate change (Lehmann *et al*., 2013).

Chapter 3 MATERIALS AND METHODS

Two field trials were conducted at Agronomic Research Area, University of Agriculture, Faisalabad (latitude 31° 26´ N, longitude 73° 04´ E and 184 m above sea level) during Rabi season of two consecutive years 2010-2011 and 2011-2012 to study the effect of different irrigation regimes, nitrogen levels and planting dates on growth and yield of wheat by using CERES-Wheat model.

3.1 Soil Analysis

Before sowing of crop, ten composite samples were obtained with soil auger from different places of experimental area. The samples were mixed thoroughly to obtain a composite sample which was analyzed for its physico-chemical properties (Table 3.1).

Mechanical Analysis

Bouyoucos hydrometer method was used to determine the percentage of sand, silt and clay by using 1% hexametaphosphate as a dispersing agent. International textural triangle was used to determine the textural class of soil (Moodie *et al.*, 1959).

Chemical Analysis

Method described by Homer and Pratt (1961) was used to analyze the soil samples for its various chemical properties.

Table 3.1: Physicochemical properties of the soil (0 – 30 cm)

Soil Characteristic	Unit	Year 2010-11	Year 2011-12
pH	--	8.50	8.45
Organic matter	(%)	0.49	0.51
Total soluble salt	(me L^{-1})	3.9	3.8
Nitrogen	(%)	0.031	0.034
Phosphorous	(mg kg^{-1})	6.93	6.95
Potassium	(mg kg^{-1})	102	106
Sand	(%)	60	60
Silt	(%)	16	16
Clay	(%)	24	24

3.2 Design and Treatment of Experiment-I

The experiment was laid out in randomized complete block design with split plot arrangement keeping fertilizer levels in main plots and irrigation levels in sub plots. Irrigation scheduling was based on critical growth stages of wheat. The net plot size was 1.2m X 10m with three replications. Fig 3.1 shows experimental design of the experiment-I.

(A) Nitrogen Levels (main plots)

F_1: 80 kg ha^{-1}

F_2: 120 kg ha^{-1} (Recommended)

F_3: 160 kg ha^{-1}

(B) Irrigation Levels (sub plots)

I_1: Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2: Irrigation at Stem Elongation, Booting and Grain Formation

I_3: Irrigation at Tillering, Stem Elongation and Grain Formation

I_4: Irrigation at Tillering, Stem Elongation and Booting

I_5: Irrigation at Tillering and Stem Elongation

I_6: Irrigation at Stem Elongation and Booting

3.3 Crop Husbandry Experiment-I:

Rotavator was used to chop and mix the stubbles of remaining crop. After Rauni irrigation, when soil was at proper moisture level, three cultivations followed by planking, were done to prepare the final seed bed. Sahar-2006 was used as a test cultivar. During both years, sowing was done in the 2nd week of November and Phosphorus and Potassium fertilizer applied at recommended rate (90:60 kg PK ha^{-1}). Nitrogen was applied according to the treatment. Single row hand drill was used for sowing with row to row distance of 20cm. Recommended seed rate (125 kg ha^{-1}) was used. Phosphorus and potassium were applied at the time of land preparation and nitrogen was applied in two split doses. Source of N, P and K were Urea, DAP (Di-Ammonium Phosphate) and SOP (Sulphate of Potash) respectively. All other cultural practices like weeding, intercultural practices etc. were kept uniform for all the experimental treatments. Table 3.2 and 3.3 indicate different agronomic practices during the seasons.

Lay Out

Exp. 1: Effect of nutrient management and irrigation regimes on growth, development, radiation use efficiency and yield of wheat.

Sub-Water Channel																				
Replication I	F_1						F_3						F_2						N.E.A.	Main Water Channel
	I_6	I_4	I_2	I_1	I_5	I_3	I_1	I_2	I_3	I_4	I_5	I_6	I_5	I_3	I_2	I_1	I_6	I_4		
Path																				
Replication II	F_3						F_2						F_1						N.E.A.	
	I_5	I_3	I_2	I_1	I_6	I_4	I_6	I_4	I_2	I_1	I_5	I_3	I_1	I_2	I_3	I_4	I_5	I_6		
Sub-Water Channel																				
Replication III	F_2						F_1						F_3						N.E.A.	
	I_1	I_2	I_3	I_4	I_5	I_6	I_5	I_3	I_2	I_1	I_6	I_4	I_6	I_4	I_2	I_1	I_5	I_3		
Path																				

Treatments:	Design: Split Plot Design
Factor A: Fertilizer (Main-Plot)	Replication: 3
F_1: 80 kg N ha^{-1}	Net Plot Size: 1.2m x 8m
F_2: 120 kg N ha^{-1} (Recommended)	R X R Distance: 20 cm
F_3: 160 kg N ha^{-1}	Seed Rate: 125 kg ha^{-1}
	Variety: Sehar-2006
Factor B: Irrigation (Sub-Plot)	Sowing Date: Mid November

I_1: Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2: Irrigation at Stem Elongation, Booting and Grain Formation

I_3: Irrigation at Tillering, Stem Elongation and Grain Formation

I_4: Irrigation at Tillering, Stem Elongation and Booting

I_5: Irrigation at Tillering and Stem Elongation

I_6: Irrigation at Stem Elongation and Booting

Table 3.2: Crop husbandry operations in experiment-I during 2010-11 and 2011-12

Operations	2010-11	2011-12
Sowing dates	15.11.2010	15.11.2011
Crop establishment	24.11.2010	22.11.2011
Fertilizer application		
P (DAP) @ 90 kg ha^{-1}	15.11.2010	15.11.2011
K (SOP) @ 60 kg ha^{-1}	15.11.2010	15.11.2011
N (Urea)		
1st Dose	15.11.2010	15.11.2011
2nd Dose	14.01.2011	13.01.2012
Sampling dates		
1	30.12.2010	30.12.2011
2	14.01.2011	14.01.2012
3	29.01.2011	29.01.2012
4	13.02.2011	13.02.2012
5	28.02.2011	28.02.2012
6	15.03.2011	14.03.2012
7	30.03.2011	29.03.2012
Harvesting	27.04.2011	30.04.2012

Table 3.3: Rainfall received and irrigation applied to different treatments in Exp 1.

Irrigation no.	Date	**I_1 (mm)**	**I_2 (mm)**	**I_3 (mm)**	**I_4 (mm)**	**I_5 (mm)**	**I_6 (mm)**
				2010-11			
1	15.12.2010	75		75	75	75	
2	14.01.2011	75	75	75	75	75	75
3	05.02.2011	75	75		75		75
4	05.03.2011	75	75	75			
Rain fall (mm)		28	28	28	28	28	28
Total (mm)		**328**	**253**	**253**	**253**	**178**	**178**
				2011-12			
1	09.12.2011	75		75	75	75	
2	13.01.2012	75	75	75	75	75	75
3	10.02.2012	75	75		75		75
4	05.03.2012	75	75	75			
Rain fall (mm)		24	24	24	24	24	24
Total (mm)		**324**	**249**	**249**	**249**	**174**	**174**

3.4 Design and Treatment of Experiment-II

Experiment was laid out in randomizes complete block design with split plot arrangement keeping sowing date in main plots and irrigation regimes in sub plots. Each plot having a net plot size of 1.2m X 8m was replicated thrice. Fig 3.2 shows common sowing plan of the experiment.

(A) = Sowing Date (main plots)

SD_1 = 15th November (Recommended)

SD_2 = 15th December

(B) = Irrigation Levels (sub plots)

I_1 = Irrigation at Tillering, Stem Elongation Booting and Grain Formation

I_2 = Irrigation at 45mm PSMD (Potential Soil Moisture Deficit)

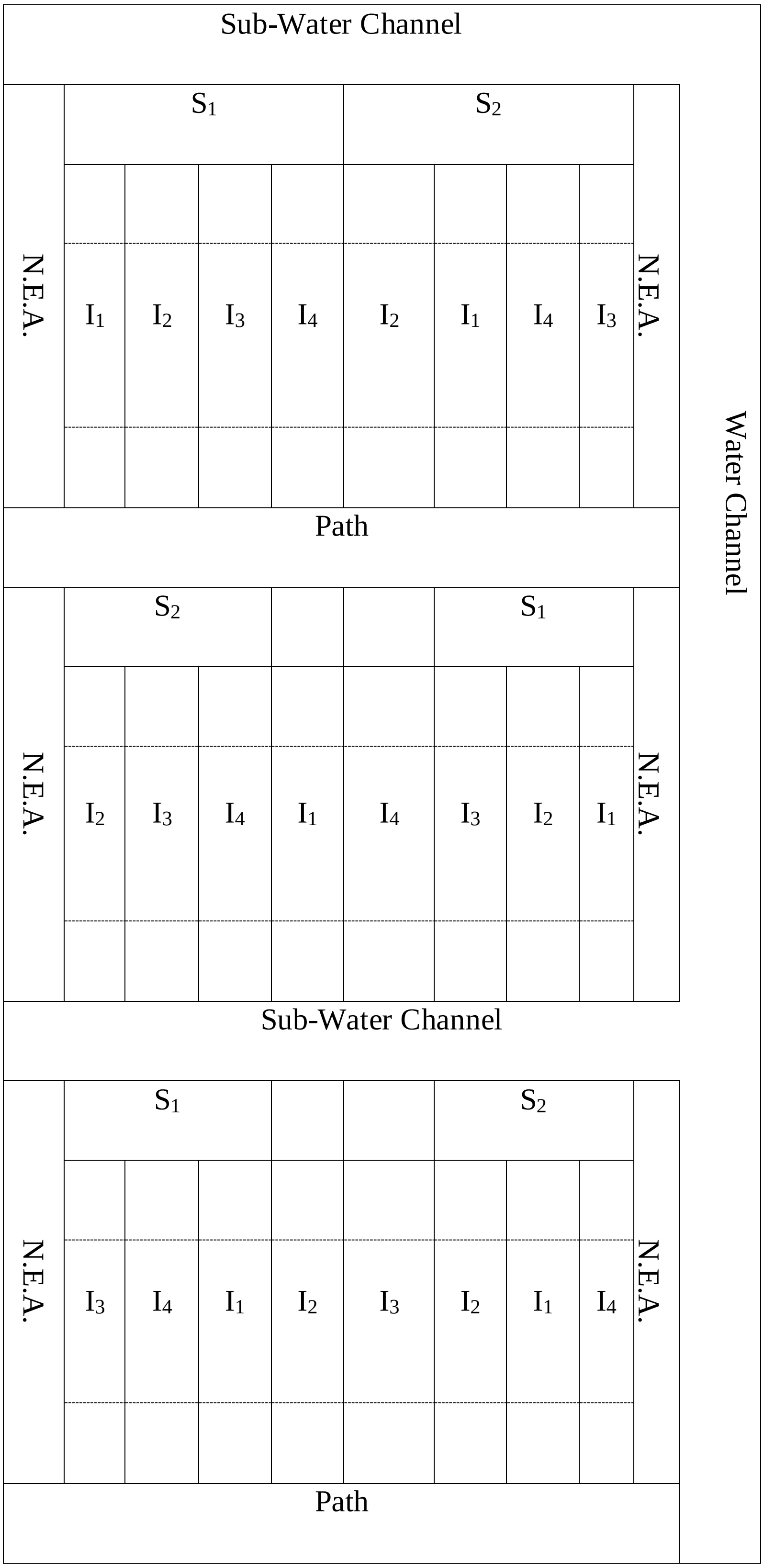
I_3 = Irrigation at 60mm PSMD (Potential Soil Moisture Deficit)

I_4 = Irrigation at 75mm PSMD (Potential Soil Moisture Deficit)

3.5 Crop Husbandry of Experiment-II

Rotavator was used to chop and mix the stubbles of remaining crop. After Rauni irrigation, when soil was at proper moisture level, three cultivations followed by planking, were done to prepare the final seed bed. Sowing was done according to the treatments. Nitrogen, Phosphorus and Potassium fertilizer applied at recommended rate (120:90:60 kg NPK ha^{-1}). Sehar-2006, a promising cultivar was used. Single row hand drill was used for sowing with row to row distance of 20cm. Recommended seed rate (125 kg ha^{-1}) was used. Phosphorus and potassium were applied at the time of land preparation and nitrogen was applied in split doses. Source of N, P and K were Urea, DAP (Di-Ammonium Phosphate) and SOP (Sulphate of Potash) respectively. All other cultural practices like weeding, intercultural practices etc. were kept uniform for all the experimental treatments.

Exp. II: Effect of planting time and deficit irrigation on growth, development, radiation use efficiency and yield of wheat.



Factor A: Sowing Dates (Main Plot)

D_1: 15^{th} Nov

D_2: 15^{th} Dec

Design: Split Plot Design

Replication: 3

Net Plot Size: 1.2m x 8m

R X R Distance: 20 cm

Seed Rate: 125 kg ha^{-1}

Variety: Sehar-2006

Factor B: Irrigation (Sub-Plot)

I_1: Full Irrigation (Control)

I_2: Irrigation at 45 mm potential soil moisture deficit

I_3: Irrigation at 60 mm potential soil moisture deficit

I_4: Irrigation at 75 mm potential soil moisture deficit

Table 3.4: Crop husbandry operations in experiment-II during 2010-11 and 2011-12

Operations	2010-11		2011-12	
	SD_1	**SD_2**	**SD_1**	**SD_2**
Sowing dates	15.11.2010	14.12.2010	15.11.2011	16.12.2011
Crop establishment	24.11.2010	27.12.2010	22.11.2011	27.12.2011
		Fertilizer application		
Nitrogen	15.11.2010	14.12.2010	15.11.2011	16.12.2011
Phosphorus	15.11.2010	14.12.2010	15.11.2011	16.12.2011
Potash	15.11.2010	14.12.2010	15.11.2011	16.12.2011
Sampling dates				
1	30.12.2010	28.01.2011	30.12.2011	30.01.2012
2	14.01.2011	12.02.2011	14.01.2012	14.02.2012
3	29.01.2011	27.02.2011	29.01.2012	29.02.2012
4	13.02.2011	14.03.2011	13.02.2012	15.03.2012
5	28.02.2011	29.03.2011	28.02.2012	30.03.2012
6	15.03.2011	13.04.2011	14.03.2012	14.04.2012
7	20.03.2011	28.04.2011	29.03.2012	29.04.2012
Harvesting	27.04.2011	11.05.2011	30.04.2012	30.04.2012

Table 3.5: Rainfall received and irrigation applied to different treatments in Exp 1

	I_1 mm	I_2 mm	I_3 mm	I_4 mm		I_1 mm	I_2 mm	I_3 mm	I_4 mm
	SD_1= 15th November					**SD_2= 15th December**			
					2010-11				
15/12/2010	75	60	60	60					
14/01/2011	75								
20/01/2011		40			20/01/2011	75	60	60	60
27/01/2011			45		14/02/2011	75	45		
05/02/2011	75			60	27/02/2011			45	
14/02/2011		45			05/03/2011	75	45		50
27/02/2011			40		12/03/2011				
05/03/2011	75	45			19/03/2011		45	45	
12/03/2011				50	26/03/2011	75			60
19/03/2011		40	50		02/04/2011		45	55	
Rain	28	28	28	28	Rain	29	29	29	29
Total	**328**	**258**	**223**	**198**	**Total**	**329**	**269**	**234**	**199**
					2011-12				
09/12/2011	75	60	60	60					
08/01/2012		40							
15/01/2012	75				17/01/2011	75	60	60	60
24/01/2012			45		12/02/2011	75	45		
31/01/2012				60	27/02/2011			45	
07/02/2012	75	45			07/03/2011	75	40		50
18/02/2012			40		12/03/2011				
28/02/2012		45		50	21/03/2011		45	40	
06/03/2012	75		55		28/03/2011	75			60
14/03/2012		45			05/04/2011		45	60	
Rain	14	14	14	14	Rain	21	21	21	21
Total	**314**	**249**	**214**	**184**	**Total**	**321**	**256**	**226**	**191**

3.6 IRRIGATION SCHEDULING

In Experiment 1, irrigation scheduling was based on critical growth stages during which the measured quantity of water was applied (as stated in the treatments) with the help of Cut Throat Flume. In Experiment 2, irrigation treatments were based on potential soil moisture deficit (PSMD) which was calculated as a difference between potential evapotranspiration (PET) and rainfall plus irrigation (I+R). Same calculated amount of irrigation water was applied (with the help of cut throat flume, Fig 3.3) as much lost by plant from root zone. For example, we applied 45mm depth of water when potential soil moisture deficit (PSMD) reaches 45mm and similar was the case with 60mm PSMD and 75mm PSMD.

Potential Soil Moisture Deficit (PSMD) was calculated from the following equation as a difference between water lost by plant in the form of potential evapo-transpiration (PET) and water received in the form of irrigation and rainfall (I+R).

$$[PSMD = PET – (I+R)]$$

Potential Evapo-Transpiration (PET) was calculated by using CROPWAT 8.0 (by FAO) based on Modified Penman-Monteith Formula. Daily weather data (maximum temperature, minimum temperature, relative humidity, wind speed and bright sunshine hours) required as input data CROPWAT 8.0 were collected from the Meteorological Observatory of Department of Crop Physiology, University of Agriculture, Faisalabad, located within the 1 km premises of Research Area.

Calculation for Quantity of Water

Cut throat flume was used to calculate the discharge of the watercourse and the following formula was used for calculation of time for a specific depth of water as cited by Choudhry (2008).

$$t = A \times d/Q$$

Where t = time to irrigate (s)

A = area of the plot to be irrigated (m^2)

d = depth of water to be applied (m)

Q = discharge of the cut throat flume (m^3)

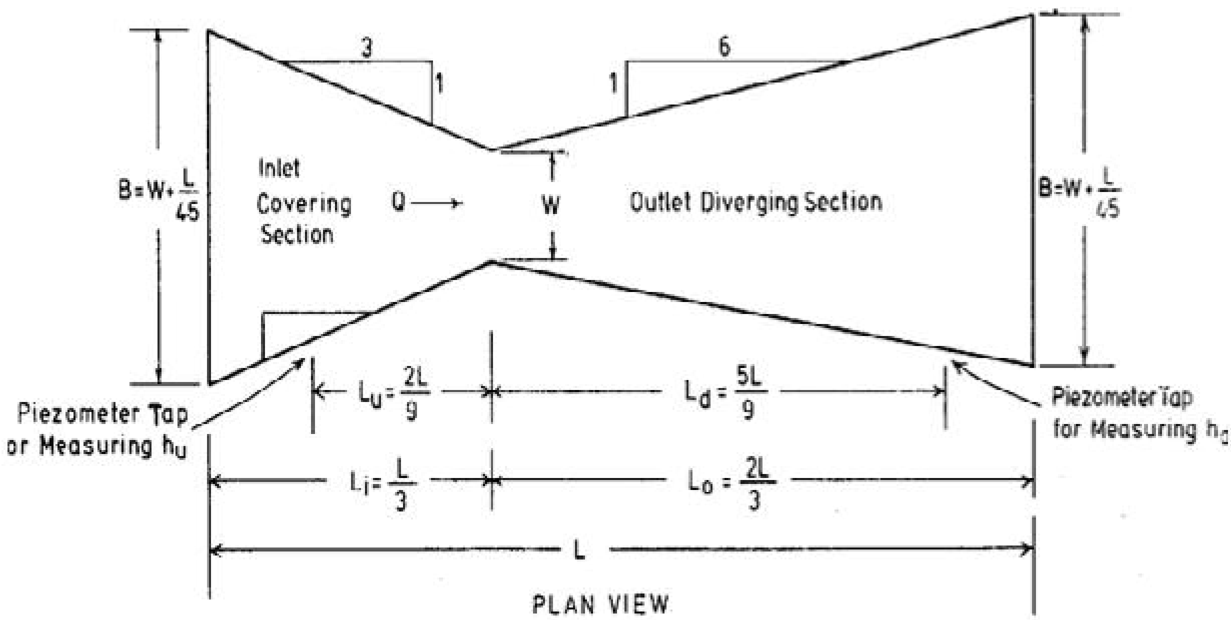


Fig: 3.3: Crass section of a Cut Throat Flume which was used for measuring irrigation regimes

3.7 CROP DEVELOPMENT

All the development stages were defined when 50% of the plants showed visual signs of the stage being considered. After germination, five plants of each plot were tagged to study the calendar days of following growth stages.

1. Seedling establishment
2. Anthesis
3. Physiological maturity

Thermal time (growing degree days) was calculated according to the method of Gallagher and Biscoe (1978). It calculates thermal time (Tt) as a function of mean temperature above a base temperature (Tb).

$$\mathrm{Tt} = \sum_{t=1}^{n}\left[\frac{(Tit + Txt)}{2} - Tb\right]$$

Where Ti and Tx are minimum and maximum daily maximum temperature and Tb is base temperature taken as 5° C for wheat (FAO, 1978).

3.8 CROP GROWTH

OBSERVATIONS

Each plot was divided into two parts. One part was used for destructive sampling to estimate biomass and leaf area production. Other part remained intact for yield components and final grain yield determination. Observations regarding total dry matter (TDM) and leaf area were made fortnightly.

SAMPLING

From each plot, half meter long row was harvested at ground level fortnightly leaving appropriate borders. Fresh weight of leaf and stem was determined by using Digital Electronic Balance. Component fractions of plant (leaf and stem) were dried in oven (Model: WFO-600ND, EYELA windy oven, Ser. No. 66066114) at 70 ^{0}C for 48 hours and dry weight was taken. Leaf area was recorded on leaf area meter (Model CI-202, CID, Inc.) by using a 10g sub-sample of green leaf laminae. Following growth parameters were calculated from the measurements of leaf area and dry weight.

LEAF AREA INDEX

Leaf area index was calculated as the ratio of leaf area to land area (Watson, 1947).

$$LAI = \text{leaf area} / \text{covered land area}$$

LEAF AREA DURATION (Days)

Leaf area duration (LAD) was estimated as suggested by Hunt (1978).

$$LAD = (LAI_1+LAI_2) \times (t_2-t_1) / 2$$

Where LAI_1 and LAI_2 are the leaf area indices at time interval of t_1 and t_2, respectively.

CROP GROWTH RATE (g m^{-2} d^{-1})

Crop growth rate (CGR) were calculated as proposed by Hunt (1978).

$$CGR = (W_2-W_1) / (t_2-t_1)$$

Where W_1 and W_2 are the dry weight harvested at time interval of t_1 and t_2, respectively.

3.9 GRAIN GROWTH

At anthesis till maturity, five spikes from each plot were choosen at random to estimate individual grain weight twice weekly. Samples were threshed manually and oven dried at 70°C for 48 hours to determine average grain weight. The rate of grain growth was determined by using the technique of Sofield *et al*. (1977). A line of best fit (maximizing R^2) for linear phase of grain growth was estimated by the least square method. The slope of the resulting line was used as the rate of grain growth. The duration of grain growth was estimated as:

Duration = Grain Growth / Rate of Grain Growth

3.10 RADIATION USE EFFICIENCY (g MJ^{-1})

Radiation use efficiency for TDM (RUE_{TDM}) and grain yield (RUE_{GY}) were calculated as the ratio of total biomass and grain yield to cumulative intercepted PAR ($\sum$ Sa).

$$RUE_{TDM} = TDM / \sum Sa$$

$$RUE_{GY} = \text{Grain yield} / \sum Sa$$

The fraction of intercepted radiation (Fi) was calculated by Beer's law as suggested by Monteith and Elston (1983) and TDM is total dry matter recorded at final harvest.

$$Fi = 1 - \exp(-k \times LAI)$$

Where k is an extinction coefficient for total solar radiation equal to 0.4 for wheat (Lindquist *et al.*, 2005).

The amount of intercepted PAR (Sa) was determined by multiplying values of Fi with daily incident PAR (Si), during the season.

$$Sa = Fi \times Si$$

The amount of total PAR intercepted by the crop was calculated by multiplying Fi with 0.5 PAR of incident radiation (Szeicz, 1974).

3.11 WATER USE EFFICIENCY

Water use efficiency (WUE) for total dry matter and seed yield was calculated as ratio of yield and actual evapotranspiration (ET_a). The Et_a of the crop was calculated by multiplying the PET with crop coefficient (K_c) following Doorenbos and Pruitt (1975).

$$WUE = Y / ET_a$$

3.12 FINAL HARVEST

From each plot of each replication, selected area was harvested at maturity, leaving appropriate borders. Harvested part was threshed manually and final grain yield was determined. Final biomass was measured by adding both grain and straw yield. Yield components were measured by taking a sub-sample of 20 plants from each plot randomly and average was taken for following data:

1. Plant height (cm)
2. Number of fertile tillers m^{-2}
3. Number of spikelets per spike
4. Number of grains per spike
5. 1000 – grains weight (g)
6. Grain yield (kg ha^{-1})
7. Total dry matter (kg ha^{-1})
8. Harvest Index (%)

Following procedure for the estimation of yield and yield contributing components was followed at the final harvest:

Plant Height

Five plants were selected at random from each plot. Their height was measured from soil surface to the tip, with the help of a meter rod and the average plant height was calculated.

Number of Fertile Tillers m^{-2}

Spike bearing tillers, having grains in florets, were counted from each experimental unit from an area of 1 m^{-2} at the time of harvest.

Number of Spikelets per Spike

Number of spikelets per spike was counted from five spikes from each plot randomly and the mean value was calculated.

Number of Grains per Spike

Number of grains from the five spikes was collected and then average number of grains per spike was calculated.

1000-Grain Weight

For thousand grain weight, a sub-sample of thousand grains, sun dried upto standard moisture content, was taken with the help of Seed Counter (Model Number 801-10/C, Serial Number CO 452) and weighed on an electric balance.

`Grain Yield (kg ha^{-1})

Half plot was harvested from each plot at random avoiding the border effects. The grains were threshed by using a tractor driven mini-thrasher and weighed on an electronic balance to determine grain yield and then converted into kg ha^{-1}.

TDM (kg ha^{-1})

Final total dry matter (TDM) or biological yield was obtained by adding both sun dried grain and straw yield per unit ground area, and then it was converted into kg ha^{-1}.

Harvest Index (%)

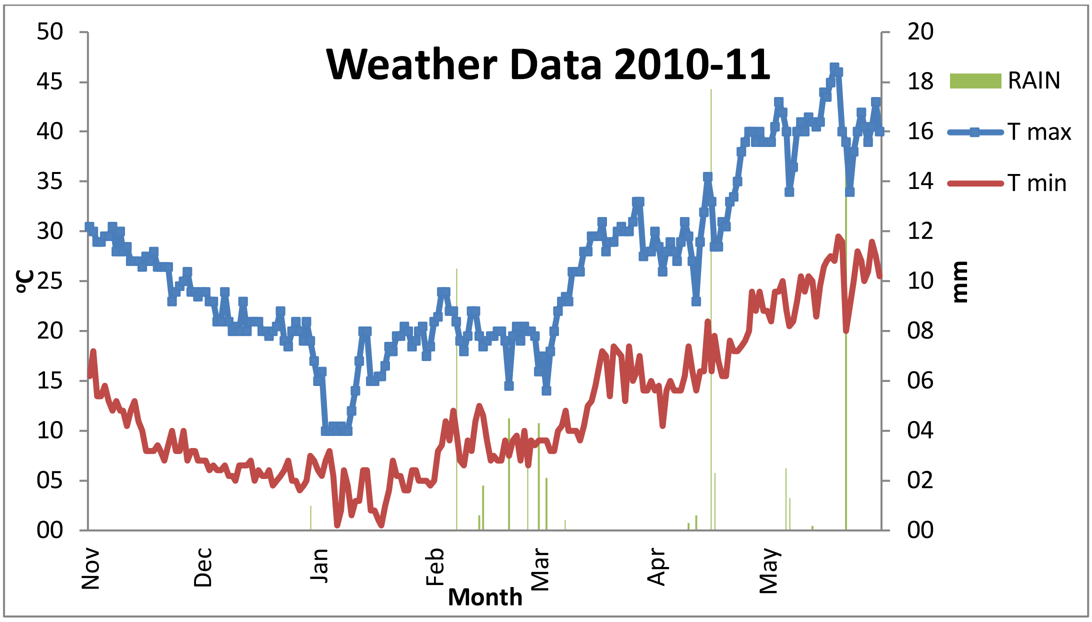
Harvest index was calculated as the ratio of grain yield to total biomass at final harvest and expressed in percentage.

3.13 WEATHER DATA

Weather data (Fig 3.4) were obtained from the Metrological observatory, Department of Crop Physiology, University of Agriculture Faisalabad-3800 Pakistan which was close (observatory) to the experimental place. The data collected were daily maximum and minimum air temperature (˚C), rainfall (mm), wind speed (km hr^{-1}) and daily sunshine hours (h). Moreover thirty five years data (1976-2010) on these parameters were also collected from Pakistan Meteorological Department and used as input data for CSM-CERES-Wheat.

3.14 STATISTICAL ANALYSIS

Collected data were analyzed statistically by employing Fisher's Analysis of Variance Technique and differences among treatment means were compared by using Least Significant Difference (LSD) Test at 5% probability level (Steel *et al*., 1997).



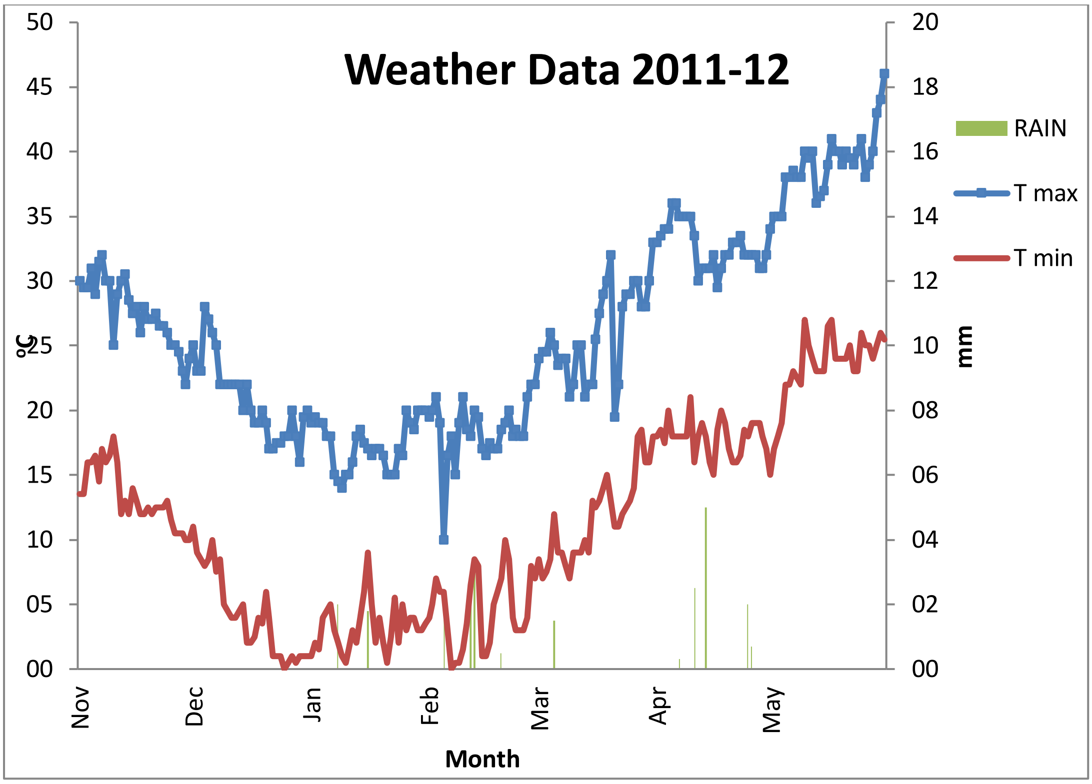


Fig. 3.4: Summary of weather conditions at experimental site during 2010-11and 2011-12

3.15 CROP GROWTH MODELING

3.15.1 Model description

Decision Support System for Agro Technology Transfer (DSSAT), a microcomputer software program (V. 4.02 shell), was used to provide an environment for calibration, evaluation and validation of CERES-Wheat Model. After successful validation process the model was used for sensitivity analysis. Daily weather observations (maximum temperature, minimum temperature, precipitation, solar radiation), site information (latitude, longitude, altitude, soil physical, chemical and morphological properties), crop management information regarding tillage, plant population, planting geometry, seed rate, sowing depth, application of irrigation, fertilizers and a set of genetic coefficients that describe cultivar in terms of development and grain biomass were required to run the model.

3.15.2 Model Calibration

Calibration is a process of adjusting some model parameters to the local conditions. It is also necessary for getting genetic coefficients for new cultivars used in modeling study. Model was calibrated with data (phenology, biomass, LAI, and yield components) collected during 2010-11 against the treatment that showed best performance in the field trials. Cultivar coefficients were determined successively starting from P1, P2, P5 and Phint (predicting flowering and maturity) followed by G1 and G2 (grain yield and yield) (Hunt and Bootie, 1998).

3.15.3 Model Evaluation

To check the accuracy of the model simulations, it was run with data recorded against remaining treatments for both experiments during the year 2010-11.

3.15.4 Model Validation

An independent set of data of year 2011-12 was used for further validation of model. During all this process, measured crop data was compared with simulated values.

3.15.5 Model statistics

Simulation performance of the model was evaluated by calculating different statistics such as root mean square error (RMSE) (Wallach and Goffinet, 1989) and mean percentage difference (MPD) for both experiments. For individual treatment level, error (%) between simulated and observed data was also calculated. The time course simulation of crop total dry matter production and leaf area index was assessed by indices of conformity (Willmott, 1982) that is cumulative over all indicators. The model statistics calculated as under as under:

$$RMSE = \left[\sum_{i=1}^{n} (p_i - o_i)^2 / n \right]^{0.5} \qquad (1)$$

$$MPD = \left[\sum_{i=1}^{n} \left(\frac{|o_i - p_i|}{o_i} \right) 100 \right] / n \qquad (2)$$

$$\text{Error (\%)} = \left(\frac{(p - o)}{o} \right) 100 \qquad (3)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (p_i - o_i)^2}{\sum_{i=1}^{n} \left(|p_i'| + |o_i'| \right)^2} \right] \qquad (4)$$

Where Pi and Oi are the predicted and observed values for studied variables, respectively and n is the number of observations. Linear regression analysis between simulated and observed grain yield and biomass at harvest was done to evaluate the performance of model. Model performance improves as R^2 and d values approach to unity while RMSE and error proceed to zero.

3.15.6 Climate Change Scenarios Generation

Climate change scenarios for different GCMs will be generated RCP 4.5 and two time span (Mid and End of Century) with the help of R by using transcripts generated by NASA and University of Columbia, USA. Thirty years historical weather data (1980-2009) will used as baseline. Daily weather data for mean and daily variability change Maximum Temperature, Minimum Temperature and Rain was generated for mid-century (2040-2069) and End of Century (2070-2099). RCP (Representative Concentration Pathway) 4.5 was designed by Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI), USA based on the concept that peak radiative force will be 4.5 W m^{-2} without over shoot and it will stabilize after 2100. Twenty GCMs were used in downscaling climate change scenarios. GCM name, its description, developing institute and country is summarized in Table 3.6 given below. Downscaled weather data were used to create new weather station and study its impact on wheat productivity. Scenarios were downscaled by following manual "Guideline for Running AgMIP Climate Scenario Generation Tool with R" version 2.3 (updated October 25th, 2013) by Alex Ruane (NASA, GISS, USA) and Nicholas Hudson (CCSR, Columbia University, USA).

3.15.7 Climate Change Impact Assessment

Field experiments were conducted to document shift in spatial boundaries of crop potential areas, changes in crop productivity and water use. So trials were conducted at Faisalabad representing semi-arid climate of Punjab and future downscaled scenarios of temperature and precipitation by different GCMs and (Table 3.5) were used for assessing the impact of climate change on wheat productivity by using crop growth model.

3.15.8 Adaptation Strategy

After assessment of climate change impact on wheat productivity, seasonal analysis tool of DSSAT was run with different management options such as irrigation, fertilizer, planting date etc. to study the potential impact of climate change and sustained crop productivity. Thirty years observed historical weather data were used for assessment of best management options to maximize grain yield.

Table 3.6: List of GCMs used for generating climate change scenarios

GCM	Model Name	Country	Center
ACCESS1-0	Australian Community Climate and Earth System Simulator, version 1.0	Australia	Centre for Australian Weather and Climate Research
			A partnership between CSIRO and the Bureau of Meteorology
csm1-1	Beijing Climate Center Climate Systems Model, 1-1	China	Beijing Climate Center, China Meteorological Administration
BNU-ESM	Beijing Normal University Earth System Model	China	Beijing Normal University (BNU)
CanESM2	Canadian Earth Systems Model, version 2	Canada	Canadian Centre for Climate Modelling & Analysis
CCSM4	Community Climate System Model, version 4	USA	National Center for Atmospheric Research (NCAR)
CESM1-BGC	Community Earth Systems Model, version 1, Biogeochemistry	USA	National Center for Atmospheric Research (NCAR)
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization Mark, version 3.6.0	Australia	Commonwealth Scientific and Industrial Research Organization (CSIRO) in collaboration with the Queensland Climate Change Centre of Excellence
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory Earth Science Model, 2G	USA	NOAA/Geophysical Fluid Dynamic Laboratory (GFDL)
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth Science Model, 2M	USA	NOAA/Geophysical Fluid Dynamic Laboratory (GFDL)
HadGEM2-CC	Hadley Centre Global Environmental Model 2, Carbon Cycle	UK	UK Meteorological Office - Hadley Centre
HadGEM2-ES	Hadley Centre Global Environmental Model 2, Earth System	UK	UK Meteorological Office - Hadley Centre
INM-CM4	Institute for Numerical Mathematics Coupled Model, version 4	Russia	Institute for Numerical Mathematics (INM)
IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace Coupled Model, version 5, coupled with NEMO, low resolution	France	Institute Pierre Simon Laplace (IPSL)
IPSL-CM5A-MR	L'Institut Pierre-Simon Laplace Coupled Model, version 5, coupled with NEMO, medium resolution	France	Institute Pierre Simon Laplace (IPSL)
MIROC5	Model for Interdisciplinary Research on Climate, version 5	Japan	University of Tokyo, NIES, JAMSTEC
MIROC-ESM	Model for Interdisciplinary Research on Climate Earth System Model	Japan	University of Tokyo, NIES, JAMSTEC
MPI-ESM-LR	Max Planck Institute Earth Systems Model, low resolution	Germany	Max Planck Institute (MPI) for Meteorology
MPI-ESM-MR	Max Planck Institute Earth Systems Model, medium resolution	Germany	Max Planck Institute (MPI) for Meteorology
MRI-CGCM3	Meteorological Research Institute Coupled General Circulation Model, version 3	Japan	Meteorological Research Institute (MRI)
NorESM1-M	Norwegian Earth System Model, version 1, intermediate resolution	Norway	Norwegian Climate Centre

Chapter 4 RESULTS AND DISCUSSION

4.1 Crop Development:

Calendar days, thermal time and photo-thermal time required by crop to complete its different growth stages during life cycle is presented in Table 4.1. Wheat crop took 139 days to complete its growth cycle in 2010-11 but its growth season was prolonged by 5 five days in 2011-12. This extension in growing season length is attributed to comparatively low temperature in 2nd year. Both the thermal and photo-thermal time was quite close in both years with a slight difference of 4 degree days.

In 2010-11, crop was germinated in 8 days and in 2011-12, germination was completed in seven days. Thermal time (101 and 105) and photo-thermal (14 and 15) was almost same in both years. Emergence to tillering initiation was completed in 22 days in 2010-11 and in 20 days 2011-12. Tillering to stem elongation phase was completed in 30 and 33 days and stem elongation to booting took place in 22 and 27 days in respective years. Although their calendar days are different in both years but their thermal time (174 and 178 for Tillering to Stem Elongation and 153 and 152 for Stem Elongation to Booting) and photo-thermal thermal time (22 and 21 for Tillering to Stem Elongation and 22 and 21 for Stem Elongation to Booting). Booting to Anthesis and Anthesis to Maturity both were completed in 28 days during both seasons. Thermal time and photo-thermal time for Booting to Anthesis was 252 and 231, 47 and 47 in both years. Thermal time was 444 and 442 and photo-thermal time was 112 and 112 for Anthesis to Maturity.

Table 4.1: Calendar days, thermal time and photo-thermal time fully irrigated and no nitrogen stress treatment in 2010-11 and 2011-12.

Crop Stages	**Calender Date**		**Calendar Days**		**Thermal Time (^oC days)**		**Photo-Thermal Time (^oC days)**	
	2010-11	**2011-12**	**2010-11**	**2011-12**	**2010-11**	**2011-12**	**2010-11**	**2011-12**
Sowing	15.11.2010	15.11.2011	0	0	0	0	0	0
Sowing to emergence	23.11.2010	22.11.2011	8	7	101	105	14	15
Emergence to Tillering	15.12.2010	12.12.2011	22	20	217	237	28	31
Tillering to Stem Elongation	14.01.2011	14.01.2012	30	33	178	174	22	21
Stem Elongation to Booting	05.02.2011	10.02.2012	22	27	153	152	22	22
Booting to Anthesis	05.03.2011	09.03.2012	28	28	252	231	47	47
Anthesis to Maturity	03.04.2011	07.04.2012	28	28	444	442	112	112
Sowing to Maturity			139	144	1361	1363	245	255

4.2 GROWTH

4.2.1 Leaf Area Index:

Year effect on maximum LAI was significant showing that plant attained higher leaf area index (4.58) for 2011-12 as compared to year 2010-11 (4.24) (Table 4.2). Fertilizer application beyond 120 kg nitrogen ha^{-1} did not show any significant increase in leaf area index but it decreased significantly when nitrogen rate was decreased to 80 kg nitrogen ha^{-1}. Same trend for nitrogen levels was observed for second year experiment. Plot receiving full irrigation (I_1= Irrigation at tillering, stem elongation, booting and grain formation) has resulted in maximum LAI of 5.27. Reducing irrigation number at different stages has highly significant reduction in maximum LAI. Plots which have irrigation stress at early growth stage (I_2= Irrigation at stem elongation, booting and grain formation; and I_6= Irrigation at stem elongation and booting) has resulted in maximum reduction in LAI. Same trend for maximum LAI was observed for irrigation treatments during year 2011-12 but higher values for LAI were recorded due to year effect.

Fig 4.1 shows changes in leaf area index with time. At earlier stage (45 days after sowing), LAI was low. With the passage of time, it starts increasing and at 90 DAS, plants attained its maximum LAI value. Plants started decreasing its LAI as it approached towards physiological maturity. In 2011-12, plant maintained higher LAI throughout its growing season as compared to 2010-11. Plots having stress at Tillering (I_2 and I_6) had lower LAI in early stage and effect of water stress at early stage cannot be compensated by later application of irrigation and LAI of early stress plot was low throughout the season as compared to full irrigation. Irrigation stress at late growth stages has resulted in higher reduction in LAI at later stage as compared to other treatments. Plots receiving 160 kg ha^{-1} Nitrogen had higher LAI throughout the growing season. Performance of plot having 120 kg ha^{-1} Nitrogen produced LAI close to plot having 160 kg ha^{-1} nitrogen while plot having 80 kg ha^{-1} Nitrogen produced lower LAI during the growing season.

Hussian *et al.* (2004) and Akram (2011) reported reduction in LAI in control treatment (establish irrigation only), followed by drought stress after booting and maximum LAI was recorded in full irrigation treatment. Tariq *et al.* (2012) reported maximum LAI on completing 80 days after sowing. Four irrigation resulted maximum LAI. Decreased irrigation frequency has significantly decreased LAI however five

Table 4.2: Effect of nitrogen rate and irrigation scheduling on maximum LAI of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	3.66 b	3.91 b	3.79
N_2= 120 (kg ha^{-1})	4.31 ab	4.7 a	4.51
N_3= 160 (kg ha^{-1})	4.74 a	5.15 a	4.95
LSD 5%	0.66	0.63	
Significance	*	*	
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	5.07 a	5.46 a	5.27
I_2= Irrigation at SE+B+GF	3.50 c	3.56 c	3.53
I_3= Irrigation at T+SE+GF	4.51 b	5.05 b	4.78
I_4= Irrigation at T+SE+B	4.82 a	5.16 ab	4.99
I_5= Irrigation at T+SE	4.27 b	4.92 b	4.60
I_6= Irrigation at SE+B	3.25 c	3.35 c	3.30
LSD 5%	0.28	0.38	
Significance	**	**	
Interaction	NS	NS	
Year Mean	4.24 b	4.58 a	
LSD 5%	0.33		
Significance	*		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

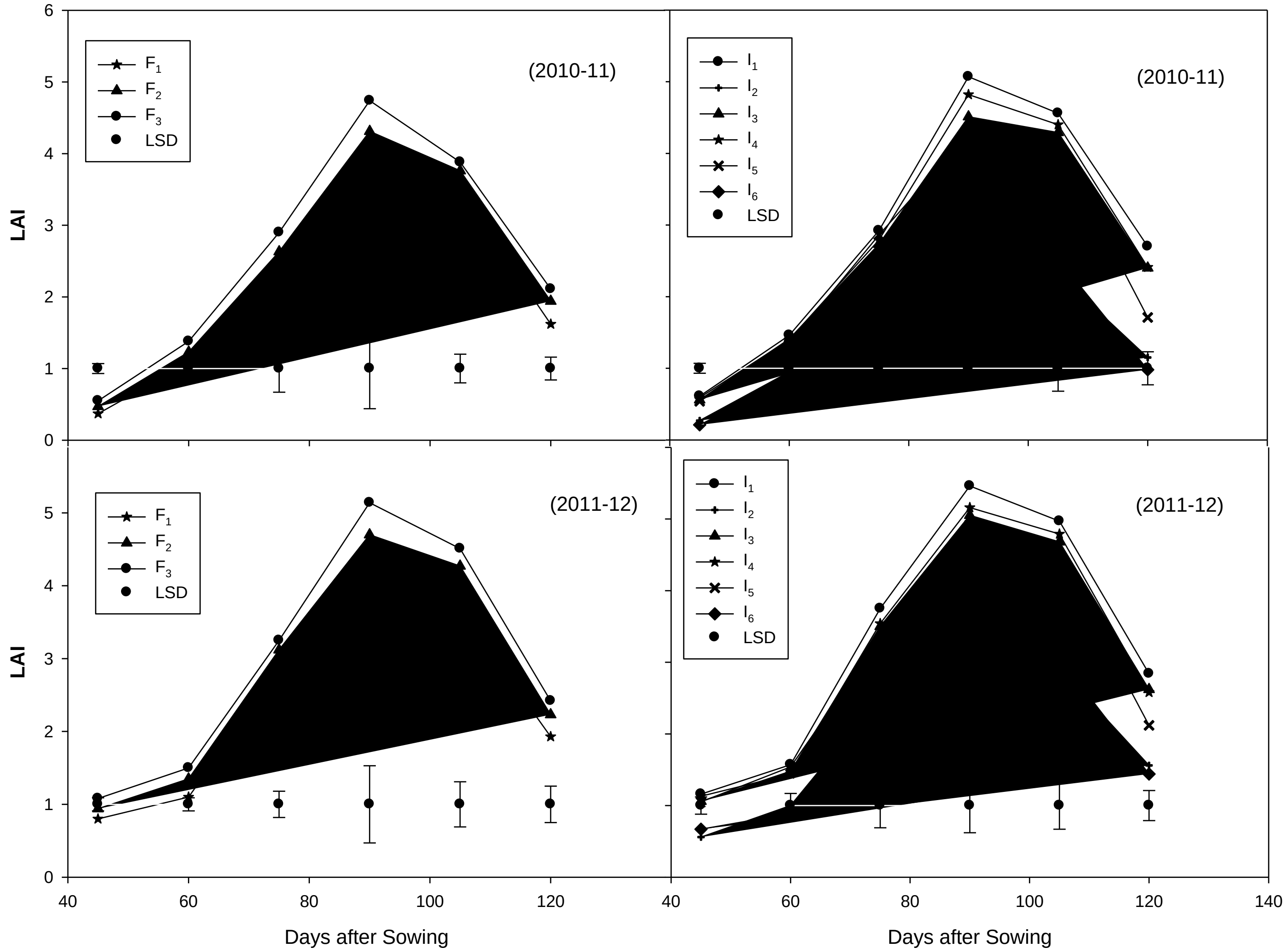


Fig 4.1: Changes in LAI with time as affected by nitrogen rate and irrigation scheduling in wheat for 2010-11 and 2011-12

irrigations did not show any significant impact in LAI as compared to four irrigations. Rehman *et al*. (2010) reported significant increase in LAI in fertilized plot as compared to control. Increase in leaf area index was due to nitrogen application delaying leaf senescence, sustaining leaf photosynthesis and extending LAD. Bavec *et al*. (2007) reported leaf area index from 1.0 to 6.5 with control to different nitrogen treatments.

4.2.2 Total Dry Matter:

Crop dry matter produced as a result of photosynthesis and nutrients uptake minus that lost by respiration is called total dry natter. Statistical analysis of year effect showed that biomass production during both growing season was statistically same (Table 4.3). Each increment in fertilizer level from 80 to 160 kg Nitrogen ha^{-1} has resulted highly significant increase in biomass. Similarly irrigation scheduling has highly significantly impact on dry matter production. Full irrigation (Irrigation at Tillering, Stem Elongation, Booting and Grain Formation) has resulted in maximum biomass production. Skipping one irrigation has decreased biomass in the following order $I_4>I_3>I_2$. Skipping two irrigations in I_5 and I_6 has resulted in minimum and statistically at par biomass production.

Figure 4.2 shows dry matter accumulation with time. At early growth stage, dry matter production was low due to cool temperature in winter. With the passage of time, as temperature start increasing, dry matter production was increased. As LAI reached its maximum value at 90 days after sowing, plant intercepted maximum light and transformed it into dry matter. Dry matter accumulation decreased as plant started losing its green color and moved towards physiological maturity.

Similar trend of biomass was reported by Shehzad *et al*. (2012) who documented the significant increase in biomass with each increment in nitrogen level. Hussain *et al*. 2006 also documented significant increase in dry matter as nitrogen rate was increased from 0 to 200 kg ha^{-1}. Wajid *et al*. (2006) reported higher biomass in plot receiving full irrigation and it decreased gradually as water stress was increased. Hussain *et al*. (2004) also reported substantially low biomass in treatments having drought stress throughout the growth stage or stress after tillering. Full irrigation has yielded maximum biomass. Tariq *et al*. (2012) reported maximum accumulation dry matter at 120 DAS. After that dry matter increased slightly or levelled off until final harvest. Decreasing irrigation number

Table 4.3: Effect of nitrogen rate and irrigation scheduling on TDM (kg ha^{-1}) of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	7768	7990	7879 c
N_2= 120 (kg ha^{-1})	8702	9008	8855 b
N_3= 160 (kg ha^{-1})	9218	9596	9406 a
LSD 5%			453
Significance			**
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	11029	11968	11499 a
I_2= Irrigation at SE+B+GF	7611	8039	7825 d
I_3= Irrigation at T+SE+GF	9534	9436	9485 c
I_4= Irrigation at T+SE+B	10000	10388	10194 b
I_5= Irrigation at T+SE	6921	6927	6924 e
I_6= Irrigation at SE+B	6281	6431	6356 e
LSD 5%			586
Significance			**
Interaction			NS
Year Mean	8563	8864	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

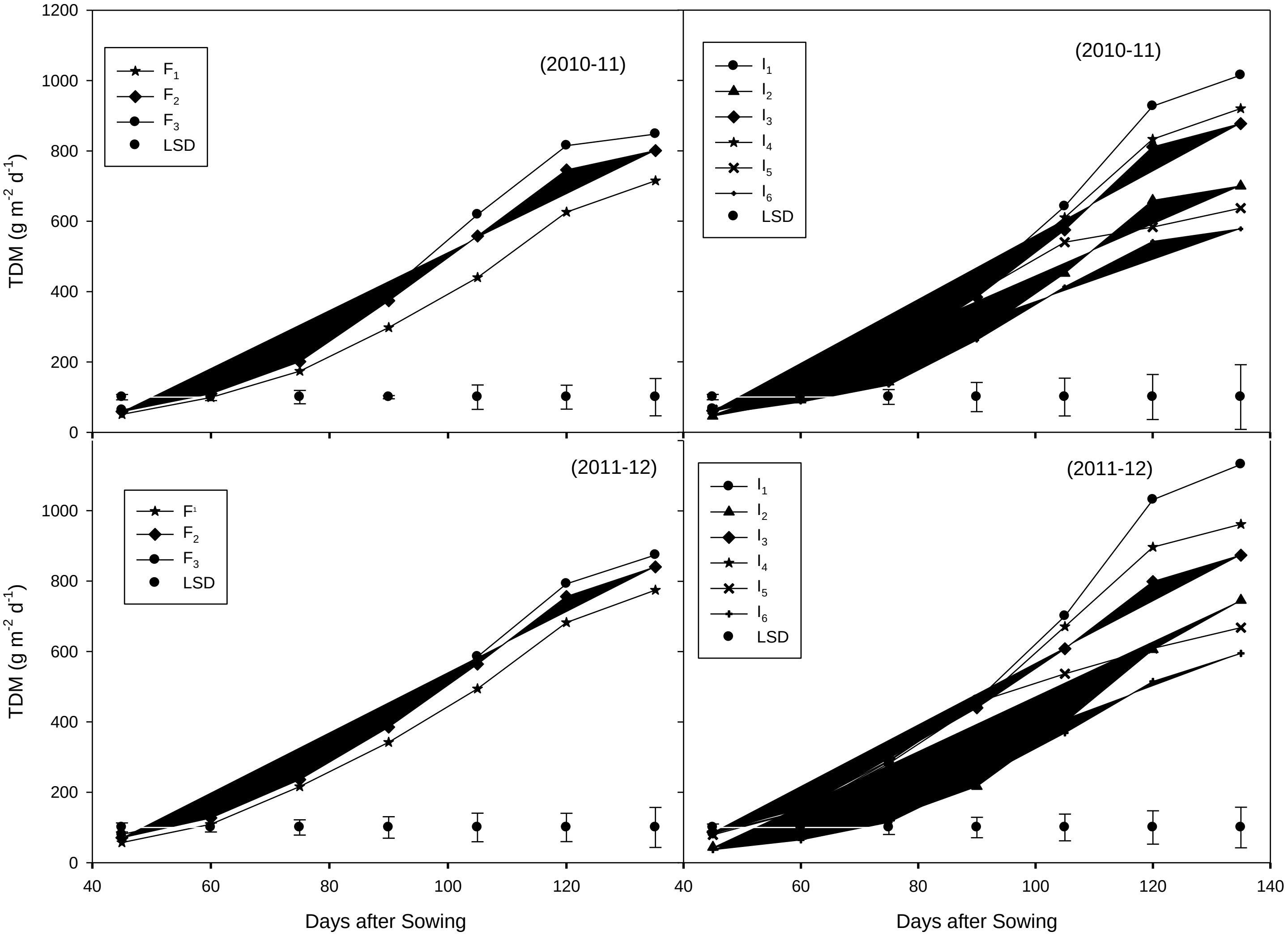


Fig 4.2: TDM accumulation with time as affected by nitrogen rate and irrigation scheduling in wheat during 2010-11 and 2011-12

from four to one has decreased biomass significantly. Five irrigation did not show any significant increase in biomass production as compared to four irrigations.

4.3 ANALYSIS OF GROWTH

4.3.1 Leaf Area Duration (LAD):

Leaf area duration is the persistency of leaf to remain green and it is calculated from leaf area index so the trend of LAI was transformed into LAD. Year analysis showed that year effect on LAD was highly significant (Table 4.4). Leaf area duration was higher in 2011-12 (220 days) as compared to 2010-11 (195) because, in second year, observed LAI was comparatively higher.

Plot received 120 and 160 kg ha^{-1} nitrogen levels performed statistically alike and low nitrogen rate (80 kg ha^{-1} Nitrogen) has significantly reduced LAD. Same trend of performance for nitrogen levels was recorded in second year.

Plot receiving full irrigation (I_1) has shown higher leaf area duration followed by irrigation treatment having stress at late (I_4) and then mid growth stage (I_3). Irrigation levels having stress at early growth stage has resulted in minimum leaf area duration (I_2 and I_6). Same pattern was recorded for irrigation levels for the year 2011-12.

Rehman *et al.* (2010) reported that delaying leaf senescence, sustained leaf photosynthesis and extended leaf area duration are the main reasons of higher leaf area index in fertilized plot as compared to controlled. Akram (2011) recorded that leaf area index reached its maximum value at 92 days after sowing and then declined towards final harvest. He also documented a significant decrease in crop receiving drought stress imposed at different growth stages as compared to full irrigation and it varied between 3.14 to 5.18. Continuous water stress from vegetative to anthesis resulted in minimum LAI. These results for nitrogen are in agreement with the findings of Asif *et al.* (2012) who calculated 234 days duration with higher fertilizer level (150 kg Nitrogen ha^{-1}).

Table 4.4: Effect of nitrogen rate and irrigation scheduling on LAD (days) of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	174 b	193 b	187
N_2= 120 (kg ha^{-1})	197 a	225 a	209
N_3= 160 (kg ha^{-1})	214 a	242 a	226
LSD 5%	17	18	
Significance	**	**	
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	235 a	266 a	249
I_2= Irrigation at SE+B+GF	147 d	166 d	154
I_3= Irrigation at T+SE+GF	216 bc	248 b	230
I_4= Irrigation at T+SE+B	224 ab	252 b	236
I_5= Irrigation at T+SE	206 c	230 c	216
I_6= Irrigation at SE+B	140 d	160 d	148
LSD 5%	14	7	
Significance	**	**	
Interaction	NS	NS	
Year Mean	195 b	220 a	
LSD 5%	7.69		
Significance	**		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

4.3.2 Crop Growth Rate:

Rate of dry matter production per unit time was statistically same during both years (Table 4.5). Crop growth rate of the plot received 120 kg ha^{-1} nitrogen was statistically at par with the plot fertilized with 160 kg nitrogen ha^{-1} but low nitrogen rate (80 kg ha^{-1} Nitrogen) has significantly reduced growth rate. Effect of irrigation scheduling on crop growth rate was highly significant. Fully irrigated plot (I_1) showed a maximum crop growth rate of 9.88 g m^{-2}. Plots receiving three irrigations (I_2, I_3 and I_4) showed a medium growth rate but it was found to be minimum in plots receiving only two irrigation (I_5 and I_6).

Guttieri *et al.* (2001) and Dalirie *et al.* (2010) documented decrease in dry matter accumulation due to terminal drought stress because it reduced LAI, lowered leaf number and hastened physiological maturity. Gul *et al.* (2013) documented maximum CGR in plot fertilizer with 130 kg ha^{-1} and it decreased as nitrogen level was decreased with minimum growth rate in plot received 0 kg nitrogen ha^{-1}. Growth rate was slow during first two months, it increased rapidly in 3rd month and it declined as crop shifted towards physiological maturity. Akram (2011) also reported higher growth rate in fully irrigated plot. Drought stress at anthesis did not decreased CGR significantly.

4.4 YIELD AND YIELD COMPONENTS

4.4.1 Plant Height:

Plant attained statistically same height during both growing season (Table 4.6). Effect of nitrogen rate on plant height was also non-significant. Significant impact of irrigation on plant height was recorded. Statistical analysis shows that fully irrigated plots have attained maximum plant height. Irrigation stress during mid and late growth stages has reduced plant height. While skipping irrigation at Tillering (I_2 and I_6) has resulted maximum reduction in plant height.

Contrary to my results, increase in plant height with increment of nitrogen rate was reported by Shehzad *et al.* (2012). They reported maximum plant height in plot recievng nitrogen 180 kg ha^{-1} and plant height decreased with the decrease in nitrogen rate to 60 kg ha^{-1}. Sarwar *et al.* (2010) have also confirmed the similar results.

Table 4.5: Effect of nitrogen rate and irrigation scheduling on mean CGR (g m^{-2} d^{-1}) of wheat

Treatment	**2010-11**	**2011-12**	**Mean**
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	6.64	7.18	6.91 b
N_2= 120 (kg ha^{-1})	7.42	7.69	7.56 a
N_3= 160 (kg ha^{-1})	7.85	7.94	7.90 a
LSD 5%			0.41
Significance			**
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	9.49	10.5	10.00 a
I_2= Irrigation at SE+B+GF	6.54	7.02	6.78 d
I_3= Irrigation at T+SE+GF	8.16	7.88	8.02 c
I_4= Irrigation at T+SE+B	8.61	8.78	8.70 b
I_5= Irrigation at T+SE	5.73	5.89	6.31 e
I_6= Irrigation at SE+B	5.28	5.57	5.43 e
LSD 5%			0.55
Significance			**
Interaction			NS
Year Mean	7.3	7.6	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

Table 4.6: Effect of nitrogen rate and irrigation scheduling on plant height (cm) of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	77.33	82.56	79.95
N_2= 120 (kg ha^{-1})	81.26	84.47	82.87
N_3= 160 (kg ha^{-1})	83.4	86.03	84.72
LSD 5%			
Significance			NS
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	85.58	90.49	88.04 a
I_2= Irrigation at SE+B+GF	75.92	78.62	77.27 c
I_3= Irrigation at T+SE+GF	82.43	86.64	84.54 ab
I_4= Irrigation at T+SE+B	84.31	89.42	86.87 ab
I_5= Irrigation at T+SE	82.29	84.14	83.22 b
I_6= Irrigation at SE+B	73.46	76.8	75.13 c
LSD 5%			4.25
Significance			**
Interaction			NS
Year Mean	80.66	84.35	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

4.4.2 Number of Spikelets per spike:

Year analysis shows that number of spikelets per spike were statistically same during both growing season. Increasing fertilizer rate from 80 to 160 Kg nitrogen ha^{-1} has not shown any impact on number of spikelets per spike. Significant impact of irrigation scheduling on number of spikelets per spike was recorded (Table 4.7). Full irrigation treatment has produced maximum number of spikelets per spike which was statistically at par with I_4 (Irrigation at Tillering, Stem Elongation and Booting). Number of spikelets per spike were reduced in I_2 and I_5 which were statistically at par with each other. Plots in which irrigation was skipped at Booting stage (I_3 and I5) have performed statistically alike and produced minimum number of spikelets per spike.

Sarwar *et al.* (2010) also reported maximum number of spikelets per spike in fully irrigated plot. Its number decreased as water was withheld at different stages. Dencic *et al.* (2000) also documented that spikelets per spike are sensitive to drought stress.

4.4.3 Number of Grains per Spike:

Interactive effect of year on number of grains per spike was statistically non-significant. Increasing fertilizer rate from 120 to 160 kg nitrogen ha^{-1} did not show any significant increase in number of grains per spike while decreasing fertilizer rate from 120 to 80 kg nitrogen ha^{-1} significantly lowered the number of grains (Table 4.8).

Deficit irrigation has significantly reduced number of grains per spike. Plot receiving full irrigation (I_1) has shown the potential of grain numbers per unit plant. As the number of grains is already defined before anthesis, so skipping irrigation at Anthesis (I_4) did not decrease number of grains and it was statistically at par with Full Irrigation. All other irrigation levels (I_2, I_3 and I_6) show reduced number of grain and performance of these treatment was statistically alike except I_5 (Irrigation at Tillering and Stem Elongation) in which water stress at Booting and Anthesis has reduced the grain number per spike to minimum.

My results are slightly contradictory with the findings of Shehzad *et al* (2012) who reported maximum grain number per spike in plot fertilized with 180 kg ha^{-1} followed by 120 kg ha^{-1} but according to my findings, increase in fertilizer from 120 to 160 kg ha^{-1} did not show any significant impact on grain number. While decrease in nitrogen below 120 kg ha^{-1} has significantly decreased grain number similar trend was

Table 4.7: Effect of nitrogen rate and irrigation scheduling on number of spikelets per spike of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	14.46	14.33	14.40
N_2= 120 (kg ha^{-1})	14.71	15.03	14.87
N_3= 160 (kg ha^{-1})	14.9	15.43	15.17
LSD 5%			
Significance			NS
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	16.26	16.92	16.59 a
I_2= Irrigation at SE+B+GF	14.81	15.44	14.85 b
I_3= Irrigation at T+SE+GF	13.41	13.59	13.50 c
I_4= Irrigation at T+SE+B	16.06	16.13	16.10 a
I_5= Irrigation at T+SE	13.01	12.61	12.81 c
I_6= Irrigation at SE+B	14.59	14.89	15.02 b
LSD 5%			1.06
Significance			**
Interaction			NS
Year Mean	14.69	14.93	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

Table 4.8: Effect of nitrogen rate and irrigation scheduling on number of grains per spike of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	29.96	30.43	30.20 b
N_2= 120 (kg ha^{-1})	34.02	34.47	34.25 a
N_3= 160 (kg ha^{-1})	36.29	36.39	36.34 a
LSD 5%			2.54
Significance			**
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	37.01	39.38	37.70 a
I_2= Irrigation at SE+B+GF	33.92	31.33	32.52 b
I_3= Irrigation at T+SE+GF	31.66	35.69	33.68 b
I_4= Irrigation at T+SE+B	36.12	36.44	36.28 a
I_5= Irrigation at T+SE	29.33	27.79	28.56 c
I_6= Irrigation at SE+B	32.5	31.94	32.22 b
LSD 5%			2.6
Significance			**
Interaction			NS
Year Mean	33.42	33.76	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

reported by Shehzad *et al* 2012. Hussain *et al.* 2006 documented significant increase in number of grains per spike in plot fertilized with nitrogen as compared to control and grain production is negatively affected by nitrogen deficiency.

4.4.4 Thousand Grain Weight:

Year analysis shows that bold grains were produced in year 2011-12 resulting in higher grain weight as compared to 2010-11 (Table 4.9). This difference in grain weight is mainly attributed to the difference in weather conditions during the growing season and particularly during grain growth stage. In year 2011-12, temperature was comparatively cool and more favorable to grain growth.

Effect of nitrogen rates on thousand grain weight was significant during both years. During year 2011-12, increasing nitrogen rate beyond 120 kg Nitrogen ha^{-1} did not show any significant increase in grain weight while reducing fertilizer rate to 80 kg nitrogen ha^{-1} has significantly lowered grain weight. In year 2011-12, grain weight of the plot fertilized with 160 kg nitrogen ha^{-1} was statistically at par with 120 kg nitrogen ha^{-1} which was statistically at par with 80 kg nitrogen ha^{-1} showing a gradual decrease in grain weight in response of decrease in nitrogen rate.

Effect of irrigation scheduling on thousand grain weight was highly significant in 2010-11 and significant during 2011-12. Maximum assimilation in grain was recorded in plot receiving full irrigation (I_1) and this irrigation level was at par with I_2 (Irrigation at Stem Elongation, Booting and Grain Formation). Water stress at different stages has reduced the grain weight. Continuous water stress from Booting to Anthesis (I_5) till maturity has reduced the grain weight to a minimum level (23.98 g). During 2011-12, plot receiving full irrigation has performed statistically similar to I_2, I_3 and I_4. Minimum thousand grain weight of 34.89 g was recorded in I_5 which was statistically similar to I_4 and I_6.

Shehzad *et al.* (2012) reported higher weight of thousand grains at 180 kg nitrogen ha^{-1}. Thousand grain weight decreased with the decrease in nitrogen rate. Similar trend was observed in my experiment. Hussain *et al.* (2006) also recorded significantly higher thousand grain weight in nitrogen sufficient plot than nitrogen deficient plot. Sarwar *et al.* (2010) recorded higher weight of the grain in fully irrigated plot due to more production and translocation of assimilates towards economic part in response to more availability of

Table 4.9: Effect of nitrogen rate and irrigation scheduling on 1000-grain weight (g) of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	27.48 b	35.21 b	31.35
N_2= 120 (kg ha^{-1})	31.71 a	39.03 ab	35.37
N_3= 160 (kg ha^{-1})	34.13 a	41.26 a	37.70
LSD 5%	4.14	3.86	
Significance	*	*	
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	36.80 a	41.16 a	38.98
I_2= Irrigation at SE+B+GF	34.02 ab	39.99 ab	37.01
I_3= Irrigation at T+SE+GF	32.92 b	40.22 ab	36.57
I_4= Irrigation at T+SE+B	28.68 c	38.17 abc	33.43
I_5= Irrigation at T+SE	24.98 d	34.89 c	29.94
I_6= Irrigation at SE+B	28.25 c	36.56 bc	32.41
LSD 5%	3.67	4.03	
Significance	**	*	
Interaction	NS	NS	
Year Mean	30.78 b	38.50 a	
LSD 5%	1.49		
Significance	**		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

water in root zone. Drought stress at different stages has decreased grain weight significantly.

4.4.5 Productive Tillers (m^{-2}):

Year analysis showed that productive tillers per unit area were alike in both growing season as indicated in Table 4.10. Fertilizer rate has highly significant impact on fertile tillers per unit area. Increasing nitrogen rate from 80 to 160 kg ha^{-1} has resulted in significant increase in productive tillers m^{-2}.

Productive tillers per unit area were highly significantly affected by irrigation scheduling. Maximum productive tillers were recorded in fully irrigation plot (I_1). Water stress at booting (I_3) show no significant reduction in number of fertile tillers and it was statistically at par with I_1. Maximum reduction in number of productive tillers were recorded in plot in which irrigation was withheld at Tillering and Grain formation (I_6) followed by plot having water stress at Tillering (I_2).

Shehzad *et al.* (2012) confirmed my results that there is a significant increase in fertile tillers by each successive increment in nitrogen fertilizer. Similar were the findings about nitrogen rates by Hussain *et al.* (2006). Sarwar *et al.* (2010) recorded 362 tillers m^{-2} in plot receiving five irrigations. Tiller number was lowered down to 278 due to water stress.

4.4.6 Grain Yield:

Grain yield is interplay of grain bearing tillers per unit area, number of grains per tiller and mean grain weight. Higher grain yield is attributed to the positive relationship of all the yield components. Effect of yield contributing components is translated into grain yield. Year effect analysis showed that significantly higher grain yield is recorded in year 2011-12 as compared to 2010-11 (Table 4.11). Effect of fertilizer rate on grain yield was highly significant in both growing season. Increasing fertilizer rate beyond 120 kg Nitrogen ha^{-1} did not show any significant increase in grain yield while fertilizer rate below the this level showed highly significant reduction in wheat productivity due to under nutrition. Similar trend was recorded for year 2011-12.

Effect of irrigation scheduling in wheat productivity was highly significant in both growing seasons. Plot receiving Full Irrigation (I_1) produced maximum grain yield due to the higher values of yield contributing components. This treatment was followed by I_3

Table 4.10: Effect of nitrogen rate and irrigation scheduling on productive tillers (m^{-2}) of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	286	303	294 c
N_2= 120 (kg ha^{-1})	308	332	320 b
N_3= 160 (kg ha^{-1})	330	342	336 a
LSD 5%			11
Significance			**
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	358	387	373 a
I_2= Irrigation at SE+B+GF	264	283	274 d
I_3= Irrigation at T+SE+GF	349	368	359 ab
I_4= Irrigation at T+SE+B	337	345	341 b
I_5= Irrigation at T+SE	300	315	307 c
I_6= Irrigation at SE+B	239	256	248 e
LSD 5%			24
Significance			**
Interaction			NS
Year Mean	308	326	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

Table 4.11: Effect of nitrogen rate and irrigation scheduling on grain yield (kg ha^{-1}) of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	2243 b	2807 b	2525
N_2= 120 (kg ha^{-1})	2834 a	3190 a	3012
N_3= 160 (kg ha^{-1})	3050 a	3334 a	3192
LSD 5%	217	243	
Significance	**	**	
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	3487 a	4463 a	3975
I_2= Irrigation at SE+B+GF	2322 c	2578 c	2450
I_3= Irrigation at T+SE+GF	3180 b	3698 b	3439
I_4= Irrigation at T+SE+B	3175 b	3430 b	3303
I_5= Irrigation at T+SE	2146 cd	2371 cd	2259
I_6= Irrigation at SE+B	1943 d	2122 d	2032
LSD 5%	261	446	
Significance	**	**	
Interaction	NS	NS	
Year Mean	2709 b	3110 a	
LSD 5%	159		
Significance	**		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

Table 4.12: Interactive effect of year and irrigation scheduling on grain yield (kg ha^{-1}) of wheat

Treatment	2010-11	2011-12
Irrigation X Year		
I_1= Irrigation at T+SE+B+GF	3487 bc	4463 a
I_2= Irrigation at SE+B+GF	2322 de	2578 d
I_3= Irrigation at T+SE+GF	3180 c	3698 b
I_4= Irrigation at T+SE+B	3175 c	3430 bc
I_5= Irrigation at T+SE	2146 ef	2371 de
I_6= Irrigation at SE+B	1943 f	2122 ef
LSD 5%	358	
Significance	*	

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

and I_4 which behave statistically alike. Skipping irrigation at Booting or Grain formation has resulted in minimum reduction in grain yield. If water stress is applied at Tillering (I_2) or Booting and Grain Formation (I_5), it resulted in higher decrease of grain yield but these two treatments were statistically at par with each other. Lowest grain yield was recorded in plot where irrigation was withheld at Tillering and Grain Formation (I_6) and it was statistically at par with I_5 (Irrigation at Tillering and Stem Elongation).

Interactive effect of Year x Irrigation was significant. Maximum grain yield was recorded in fully Irrigated plot (I_1) in year 2011-12 while grain yield was minimum and statistically at par with each other in I_5 year 2010-11 and I_6 in year 2011-12 and these treatments were statistically similar to I_2 year 2010-11 and I_5 year 2011-12 (Table 4.12).

My results are in contrary to the findings of Shehzad *et al.* (2012) who reported maximum grain yield in plot fertilized with 180 kg nitrogen ha^{-1} as compared to the plot fertilized with 120 kg nitrogen ha^{-1} but in my findings increase in fertilizer level beyond 120 kg Nitrogen ha^{-1} did not show any significant increment in grain yield. Hussain *et al.* (2006) also quoted grain yield of 5.0 t ha^{-1} with 150 kg nitrogen ha^{-1} and at 100 kg nitrogen ha^{-1} it was reduced to 4.4 t ha^{-1}. Wajid *et al.* (2006) reported higher yield in fully irrigated crop as compared to the control receiving establishment irrigation. Hussain *et al.* (2004) documented that crop having higher biomass have higher grain yield. Drought induced reduction in grain yield followed the trend similar the biomass.

4.5 RADIATION USE EFFICIENCY

4.5.1 Cumulative Intercepted Photosynthetic Active Radiation (PAR):

Table 4.13 shows that cumulative interception of PAR was significantly higher in 2011-12 with 1115 MJ m^{-2} cumulative incident PAR available to the plant. Interception of PAR was comparatively low with 1016 MJ m^{-2} of cumulative incident PAR. Plant was unable to intercept the total available PAR due to its low interception. Lower LAI at early growth stage resulted in low interception of available PAR. When plant attained its maximum LAI, interception of available PAR was maximum. Then LAI declined as it moved towards physiological maturity resulted in lesser interception of available PAR.

Nitrogen rates significantly affected the cumulative interception of PAR during the both growing season. In 2010-11, cumulative interception of PAR was same in plot fertilized with 120 and 160 kg Nitrogen ha^{-1}. Lower fertilizer level (80 kg Nitrogen ha^{-1})

Table 4.13: Effect of nitrogen rate and irrigation scheduling on cumulative interceptive PAR (g m^{-2} MJ^{-1}) of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	364 b	424 b	398
N_2= 120 (kg ha^{-1})	398 a	475 ab	435
N_3= 160 (kg ha^{-1})	421 a	498 a	458
LSD 5%	27	53	
Significance	*	*	
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	453 a (1016)	530 a (1115)	490
I_2= Irrigation at SE+B+GF	321 c	290 c	353
I_3= Irrigation at T+SE+GF	434 ab	487 b	471
I_4= Irrigation at T+SE+B	440 ab	514 ab	476
I_5= Irrigation at T+SE	411 b	488 b	448
I_6= Irrigation at SE+B	305 c	387 c	344
LSD 5%	30	28	
Significance	**	**	
Interaction	NS	NS	
Year Mean	394 b	466 a	
LSD 5%	17		
Significance	**		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

significantly reduced the amount of Intercepted PAR. In year 2011-12, increasing fertilizer rate beyond 120 kg Nitrogen ha^{-1} did not significantly increase the interception of PAR. Interception of PAR by plot receiving 120 kg Nitrogen ha^{-1} was statistically similar to the plot fertilized with 80 kg Nitrogen ha^{-1}.

Irrigation scheduling highly significant affected the interception of PAR during both growing season. Fully irrigated plot intercepted maximum PAR (453MJ) during 2011-12. Performance of this treatment was statistically similar to the plots receiving Irrigation at Tillering, Stem Elongation and Grain Formation (I_3) and Irrigation at Tillering, Stem Elongation and Booting (I_4). Interception of PAR was minimum in the plot having water stress at Tillering (I_2= Irrigation at Stem Elongation, Booting and Grain Formation). This plot was statistically similar to the plot receiving water stress at Tillering and Grain formation (I_6= Irrigation at Stem Elongation and Booting). Similar trend of interception of photo-synthetically active radiation for irrigation scheduling was recorded in 2011-12.

Interception of PAR is directly associated with the capacity of plant to intercept light which depend on LAI of crop at particular stage. Incident PAR is same for all the plots, it is the plant capacity to intercept the fraction of light. If LAI is low either due to lower Nitrogen rate or water stress at Tillering stage, interception of available PAR is highly reduced.

Hussain *et al*. (2004) calculated a variation in PAR by 8-10% among different drought treatments. Maximum accumulated PAR varied from 430 to 470 MJ m^{-2}. Tariq *et al*. (2012) documented the interception of 488-510 MJ^{-1} m^{-2} PAR (45-47% to total available PAR) in fully irrigated crop in two year experiment. Fully irrigated crop intercepted higher units of cumulative PAR as compared to partially irrigated crop.

4.5.2 Radiation Use Efficiency for Grain Yield:

Year analysis shows that RUE for grain yield was higher in 2010-11 as compared to 2011-12. Interception of PAR was high in 2011-12 but its conversion efficiency was low and vice versa for 2010-11. Nitrogen rates significantly affected RUE for grain yield in 2010-11 but its effect was non-significant in 2011-12. In first year, plot receiving 120 kg Nitrogen ha^{-1} showed maximum radiation use efficiency (0.71 g m^{-2} Mj^{-1}) and increasing fertilizer rate to 160 kg Nitrogen ha^{-1} has not significantly increased RUE. But lowering nitrogen rate from 120 to 80 kg Nitrogen ha^{-1} has significantly reduced RUE for grain yield (4.14).

Radiation use efficiency for grain yield was highly significantly affected by irrigation scheduling in both growing season. In year 2010-11, Full irrigation (I_1) and plots having waster stress at any one growth stage (I_2, I_3 and I_4) has shown maximum and statistically at par efficiency to produce grain biomass by intercepting one unit of PAR in area of one square meter. Efficiency of transformation of intercepted PAR in unit area was least (0.52 g m^{-2} MJ^{-1}) in the plot where drought stress was applied at Booting and Grain formation (I_5= Irrigation at tillering and Stem Elongation).

In 2011-12, fully irrigated plot (I_1) has converted the intercepted light into grain yield with maximum efficiency (0.84 g m^{-2} MJ^{-1}). Plot receiving three irrigation and water withheld at one stage (I_2, I_3 and I_4) performed statistically alike in conversion of photo-synthetically active radiation into grain yield. Radiation use efficiency was minimum and statistically same in plots receiving only two irrigations (I_5 and I_6).

Findings are in partial agreement with Shehzad *et al.* (2012) who reported maximum RUE in plot fertilized with 180 kg Nitrogen ha^{-1} and it decreased significantly with each decrease in nitrogen level but according to my findings 120 and 160 kg Nitrogen ha^{-1} performed alike in 2010-11 and decrease in nitrogen below 120 kg Nitrogen ha^{-1} decreased RUE significantly. Tariq *et al.* (2012) calculated maximum RUE with four irrigations at crown root, booting, anthesis and grain formation in hotter environment. It decreased with the decrease in number of irrigations at different stages. It ranged from 0.69 to 0.97 g m^{-2} MJ^{-1} as irrigation frequency was increased from 1 to 4 and it again decreased to 0.96 g m^{-2} MJ^{-1} as irrigation number was increased to five.

Table 4.14: Effect of nitrogen rate and irrigation scheduling on RUE for grain yield (g m^{-2} MJ^{-1}) of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	0.61 b	0.64	0.62
N_2= 120 (kg ha^{-1})	0.71 a	0.67	0.68
N_3= 160 (kg ha^{-1})	0.72 a	0.66	0.70
LSD 5%	0.07		
Significance	*	NS	
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	0.77 a	0.84 a	0.80
I_2= Irrigation at SE+B+GF	0.72 a	0.66 b	0.69
I_3= Irrigation at T+SE+GF	0.73 a	0.73 b	0.73
I_4= Irrigation at T+SE+B	0.72 a	0.67 b	0.69
I_5= Irrigation at T+SE	0.52 c	0.49 c	0.51
I_6= Irrigation at SE+B	0.63 b	0.55 c	0.59
LSD 5%	0.08	0.1	
Significance	**	**	
Interaction	NS	NS	
Year Mean	0.68 a	0.65 b	
LSD 5%	0.01		
Significance	*		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

4.5.3 Radiation Use Efficiency for TDM:

Radiation use efficiency was significant and higher in 2010-11 as compared to 2011-12 (Table 4.15). Fertilizer rate did not show any effect on efficiency of crop to convert light into biomass in both growing season. But irrigation scheduling significantly affected radiation use efficiency for dry matter production. In 2010-11, 2.43 g of biomass production was recorded by utilizing one mega joule of PAR in areas of one square meter in fully irrigated plot (I_1). Performance of this plot for RUE for biomass was statistically similar to I_2, I_3 and I_4. Radiation use efficiency was reduced to the least in plot irrigated at Tillering and Stem Elongation (I_5). In year 2011-12, maximum biomass of 2.26 g per unit area by intercepting one unit of PAR was recorded in plot fully irrigated throughout the growing season (I_1). Stress at Tillering (I_2) and stress at grain formation (I_4) has reduced RUE for biomass production followed the plot having stress at booting (I_3). Double stress at Tillering and Grain Formation (I_6) has further reduced radiation use efficiency. Efficiency of conversion of light into biomass was minimum (1.42 g m^{-2} Mj^{-1}) in plot received irrigation at Tillering and Stem Elongation (I_5).

My results are in contrast to the findings of Shehzad *et al.* (2012) who documented higher RUE for plot fertilized with 180 kg ha^{-1} and it was decreased with decreasing nitrogen level. Results of irrigation scheduling are in agreement with the findings of Hussain *et al.* (2004) who measured maximum RUE for biomass 2.71 and 1.99 g MJ^{-1} in two year experiment. Water stress resulted significant reduction in biomass production by changing the amount of intercepted PAR. The variation in maximum RUE is explained by variation in maximum interception of PAR. According to Monteith (1977) biomass production is directly related to interception of PAR. Fraction of intercepted radiation increases hyperbolically with LAI and reaches to 90% or above when LAI becomes 4-6 (Monteith and Elston, 1983). Results have shown that the reduction in biomass production caused by variation in RUE is substantially higher than the variation in PAR interception. Early drought stress showed substantial reduction in RUE and it persisted throughout the growing season length.

Table 4.15: Effect of nitrogen rate and irrigation scheduling on RUE for TDM (g m^{-2} MJ^{-1}) of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	2.16	1.83	2.06
N_2= 120 (kg ha^{-1})	2.18	1.89	2.06
N_3= 160 (kg ha^{-1})	2.17	1.92	2.05
LSD 5%			
Significance	NS	NS	
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	2.43 a	2.26 a	2.34
I_2= Irrigation at SE+B+GF	2.39 a	2.06 b	2.23
I_3= Irrigation at T+SE+GF	2.19 ab	1.85 c	2.02
I_4= Irrigation at T+SE+B	2.27 ab	2.01 b	2.14
I_5= Irrigation at T+SE	1.69 c	1.42 e	1.56
I_6= Irrigation at SE+B	2.07 b	1.66 d	1.87
LSD 5%	0.28	0.15	
Significance	**	**	
Interaction	NS	NS	
Year Mean	2.17 a	1.87 b	
LSD 5%	0.13		
Significance	**		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

4.6 WATER USE EFFICIENCY

Water use efficiency to produce grain yield by utilizing one unit of water evapo-transpired by the plant was statistically higher in 2011-12 as compared to 2010-11. Effect of fertilizer rate on water use efficiency was highly significant in 2010-11 and significant in 2011-12. In first year, increasing fertilizer rate from 120 to 160 kg Nitrogen ha^{-1} increased WUE but it was statistically non-significant while decreasing fertilizer rate from 120 to 80 kg nitrogen ha^{-1} resulted in significant reduction in water use efficiency based on the water evapo-transpired by the crop throughout the growing season. Similar trend was recorded in year 2011-12 (Table 4.16).

Effect of irrigation scheduling was highly significant on WUE based on crop ET in both growing season. In 2010-11, 2.02 g of grain yield was produced by utilizing one millimeter of water in unit area of the plot receiving full irrigation (I_1). Performance of fully irrigated plot was similar to I_2, I_3 and I_4. Attitude of I_4 was statistically close to I_6. WUE was reduced to minimum if irrigation is withheld at Booting and Grain formation (I_5). In second year trial, fully irrigated plot (I_1) and plot in which irrigation stress was applied at Booting (I_3) produced maximum and statistically at par grain yield per unit area per unit amount of water lost in the form of ET. Water stress at different stages lowered WUE and it was reduced to minimum in treatment where water stress was applied at grain formation stage (I_5 and I_6) and performance of these two treatments was statistically same.

Wajid *et al*. (2007) reported maximum WUE (2.51 g m^{-2} mm^{-1}) in fully irrigated plot. They noted a decrease in WUE upto 1.32 g m^{-2} mm^{-1} as water was withheld after a certain stage. Similar were the findings of Sun *et al*. (2006) who recorded an increase in WUE with increase in irrigation from zero to full.

Table 4.16: Effect of nitrogen rate and irrigation scheduling on WUE (g m^{-2} mm^{-1}) based on crop ET of wheat

Treatment	2010-11	2011-12	Mean
A) Nitrogen rates (kg ha^{-1})			
N_1= 80 (kg ha^{-1})	1.48 b	1.71 b	1.59
N_2= 120 (kg ha^{-1})	1.90 a	1.94 a	1.92
N_3= 160 (kg ha^{-1})	2.04 a	2.03 a	2.03
LSD 5%	0.18	0.17	
Significance	**	*	
B) Irrigation			
I_1= Irrigation at T+SE+B+GF	2.02 a	2.32 a	2.17
I_2= Irrigation at SE+B+GF	1.98 a	1.97 b	1.97
I_3= Irrigation at T+SE+GF	1.91 a	2.06 ab	1.98
I_4= Irrigation at T+SE+B	1.88 ab	1.90 bc	1.89
I_5= Irrigation at T+SE	1.37 c	1.43 d	1.40
I_6= Irrigation at SE+B	1.70 b	1.67 cd	1.68
LSD 5%	0.19	0.29	
Significance	**	**	
Interaction	NS	NS	
Year Mean	1.81 b	1.89 a	
LSD 5%	0.03		
Significance	**		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation

I_2= Irrigation at Stem Elongation, Booting and Grain Formation

I_3= Irrigation at Tillering, Stem Elongation and Grain Formation

I_4= Irrigation at Tillering, Stem Elongation and Booting

I_5= Irrigation at Tillering and Stem Elongation

I_6= Irrigation at Stem Elongation and Booting

4.7 Economic Analysis:

Table 4.17 showed the expenditure, gross income and net return from different nitrogen rate and irrigation scheduling. In both growing season, fully irrigated crop has resulted in maximum net return and higher benefit cost ratio for all the nitrogen rates as compared to water stress treatments. Although the performance of N_2 and N_3 was statistically alike but economic analysis showed that increasing nitrogen rate from 120 to 160 kg ha^{-1} has increased net profit and benefit cost ratio. So economically use of higher fertilizer rate (N_3= 160 kg ha^{-1}) is suggested for maximum benefit. Plot having drought at tillering and grain formation (I_6= Irrigation at stem elongation and booting) is always in monetary loss due to higher expense and lower income in both years. So drought stress at tillering and grain formation should always be avoided.

On the other hand, monetary return from nitrogen is associated with the irrigation level. Increasing nitrogen rate has increased benefit cost ratio (as in I_1) and sometime higher fertilizer rate has reduced the benefit cost ratio (as in I_2 in 2010-11).

Overall, higher benefit cost ratio (1.69) was calculated in F_3I_1 in 2011-12 with maximum net return (Rs 62619). Higher grain and straw yield resulted in maximum monetary return. It was followed by the same treatment in year 2010-11 with net return and BCR of Rs 47251 and 1.51 respectively. Minimum net return (Rs -15693 and 15386) and BCR (0.78 and 0.81) was calculated in F_1I_6 in 2010-11 and 2011-12 respectively.

Table 4.17: Economic analysis for nitrogen rates and irrigation scheduling in wheat for 2010-11 and 2011-12

	Year 2010-11						Year 2011-12					
	Fixed Cost	Variable Cost	Total Cost	Gross Income	Net Return	BCR	Fixed Cost	Variable Cost	Total Cost	Gross Income	Net Return	BCR
F_1I_1	44933	30105	75038	97772	22734	1.30	47715	38418	86133	129072	42939	1.50
F_1I_2	44933	28105	73038	64660	-8378	0.89	47715	36418	84133	81504	-2628	0.97
F_1I_3	44933	28105	73038	86088	13050	1.18	47715	36418	84133	100366	16233	1.19
F_1I_4	44933	28105	73038	88071	15033	1.21	47715	36418	84133	104361	20229	1.24
F_1I_5	44933	26105	71038	65616	-5422	0.92	47715	34418	82133	73889	-8243	0.90
F_1I_6	44933	26105	71038	55345	-15693	0.78	47715	34418	82133	66746	-15386	0.81
F_2I_1	44933	31610	76543	114975	38432	1.50	47715	40868	88583	145272	56690	1.64
F_2I_2	44933	29610	74543	82458	7915	1.11	47715	38868	86583	91033	4450	1.05
F_2I_3	44933	29610	74543	103211	28668	1.38	47715	38868	86583	119445	32862	1.38
F_2I_4	44933	29610	74543	105282	30739	1.41	47715	38868	86583	119083	32500	1.38
F_2I_5	44933	27610	72543	69302	-3241	0.96	47715	36868	84583	80748	-3834	0.95
F_2I_6	44933	27610	72543	65501	-7042	0.90	47715	36868	84583	73485	-11097	0.87
F_3I_1	44933	33163	78096	125347	47251	1.61	47715	43378	91093	153711	62619	1.69
F_3I_2	44933	31163	76096	82487	6392	1.08	47715	41378	89093	95986	6893	1.08
F_3I_3	44933	31163	76096	110212	34117	1.45	47715	41378	89093	125780	36688	1.41
F_3I_4	44933	31163	76096	113814	37719	1.50	47715	41378	89093	127987	38894	1.44
F_3I_5	44933	29163	74096	75420	1325	1.02	47715	39378	87093	83525	-3568	0.96
F_3I_6	44933	29163	74096	69804	-4291	0.94	47715	39378	87093	77271	-9821	0.89

EXPERIMENT II

4.8 CROP DEVELOPMENT:

Calendar date, calendar days, thermal time and photo-thermal time for different developmental stages of wheat is presented in Table 4.18. In SD_1, crop took 139 days to complete its life cycle in 2010-11 and 144 days in 2011-12. Although calendar days were higher in second year but their thermal time (1361 and 1363 ^oC days) and photo-thermal time (245 and 255) are very close in both years. In SD_2, crop was exposed to higher temperature during later growth stage, so it completed its life cycle in short time (120 days in 2010-11 and 125 days in 2011-12) as compared to SD_1. Close values were recorded for thermal time (1215 and 1233 ^oC days) among the year but these values were slightly lower than the values recorded in SD_1 due to short growing season. Similarly photo-thermal time (252 ^oC days) in year 2010-11 was slightly close to SD_1 but in year 2011-12 it was slightly higher (278 ^oC days) than SD_1.

In 2010-11, SD_1 took 9 days to germinate but in 2011-12 it completed germination in 7 days due to relatively higher temperature. Thermal time was 112 ^oC days and 105 ^oC days for 2010-11 and 2011-12 respectively. Photo-thermal for germination was so close in both years (16 vs 15 ^oC days). In case of SD_2, calendar days, thermal time and photo-thermal time were recorded to be 13 days and 11 days, 103 ^oC days and 59 ^oC days, and 12 ^oC days and 7 ^oC days for year 2010-11 and 2011-12 respectively.

In 2010-11, crop shifted from germination to anthesis stage in 103 days but in 2011-12, it took 108 days. But their thermal time was close (808 and 794 ^oC days) photo-thermal time was same (122 ^oC days) were close in both years. Delayed sowing (SD_2) shortened the germination to anthesis stage by 19 days in 2010-11 and 20 days in 2011-12. 718 ^oC days and 662 ^oC days was the thermal time and 134 ^oC days and 127 ^oC days was the photo-thermal time for shifting of crop from germination to anthesis stage for year 2010-11 and 2011-12. Thermal time in SD_2 was lower but its photo-thermal time was much closer to that in SD_1.

Grain formation continues for 27 days in 2010-11 and 29 days in 2011-12 with a slight difference in thermal time (441 vs 464 ^oC days) and photo-thermal time (107 vs 118 ^oC days). In delayed sowing (SD_2), crop completed its grain formation stage in 23 days (4 days less as compared to SD_1) in 2010-11 and 26 days (3 days less as compared to SD_1) in 2011-12.

Table 4.18: Phenology of the wheat for two sowing dates and fully irrigated irrigation level for 2010-11 and 2011-12.

Crop Stages	Treatments	Calendar Date		Calendar Days		Thermal Time (ºC days)		Photo-Thermal Time (ºC days)	
		2010-11	2011-12	2010-11	2011-12	2010-11	2011-12	2010-11	2011-12
Sowing	S_1	15.11.2010	15.11.2011	0	0	0	0	0	0
	S_2	14.12.2010	16.12.2011	0	0	0	0	0	0
Sowing to emergence	S_1	24.11.2010	22.11.2011	9	7	112	105	16	15
	S_2	27.12.2010	27.12.2011	13	11	103	59	12	7
Emergence to Anthesis	S_1	07.03.2011	09.03.2012	103	108	808	794	122	122
	S_2	21.03.2011	24.03.2012	84	88	718	662	134	127
Anthesis to Maturity	S_1	03.04.2011	07.04.2012	27	29	441	464	107	118
	S_2	13.04.2011	19.04.2012	23	26	394	512	106	145
Sowing to Maturity	S_1			139	144	1361	1363	245	255
	S_2			120	125	1215	1233	252	278

S_1= 15th November Sowing Date

S_2= 15th December Sowing Date

There were differences among thermal time (394 and 512 ^{o}C days) and photo-thermal time (106 and 145 ^{o}C days) in year 2010-11and 2011-12 respectively.

4.9 GROWTH

4.9.1 Leaf Area Index:

Leaf area index is an important physiological determinant of crop yield. Maximum leaf area index recorded at 90 days after sowing. It is obvious from the Table 4.19 that year effect was significant showing higher value of LAI (4.69) for 2011-12 as compared to LAI (4.12) in 2010-11.

Effect of sowing date and irrigation levels was highly significant on maximum LAI during both years. Interactive effect of sowing date X year was also highly significant (Table 4.20). Crop sown on 15th November in 2011-12 produced a maximum value of LAI (5.04) which was sharing the same letter with plot sown on 15th November in 2010-11 and this treatment was statistically at par with 15th December sowing in 2011-12. 15th December sowing in 2010-11 has resulted in statistically lower LAI.

Irrigation has a direct impact on leaf area expansion Table (4.19). In 2010-11, fully irrigated plot produced higher LAI (4.65) which was statistically at par with Irrigation at 45mm PSMD (4.36). Decreasing water deficit level has decreased leaf area expansion. Lower value of maximum leaf area index (3.49) was recorded in I_4 and it is statistically similar to I_3 (3.96). Similar trend was observed in year 2011-12. High and statistically at par maximum LAI was produced with full irrigation (5.29) and I_2 (5.02). Performance of 45mm PSMD for LAI was statistically similar to 60 mm PSMD. Lowest value of maximum LAI (3.83) was recorded with I_4 (Irrigation at 75mm PSMD).

Bavec *et al.* (2007) concluded that leaf area index can be useful for prediction of grain yield. Dalirie *et al.* (2010) reported decrease in LAI when terminal stress was applied because it increased leaf aging, hastened leaf senescence and competition for resources.

4.9.2 Total Dry Matter:

Biological yield is the total dry matter produced by the plant including both economical part and by-product. It is dependent upon the interception of radiation by the

Table 4.19: Sowing date and PSMD level affecting maximum LAI in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	4.73 a	5.04 a	4.89
SD_2= 15th December	3.50 b	4.33 b	3.92
LSD 5%	0.41	0.29	
Significance	*	*	
B) Irrigation			
I_1= Full Irrigation (Control)	4.65 a	5.29 a	4.97
I_2= 45 mm PSMD	4.36 ab	5.02 ab	4.69
I_3= 60 mm PSMD	3.96 bc	4.6 b	4.28
I_4= 75 mm PSMD	3.49 c	3.83 c	3.66
LSD 5%	0.56	0.61	
Significance	**	**	
Interaction			NS
Year Mean	4.12 b	4.69 a	
LSD 5%	0.51		
Significance	*		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

Table 4.20: Interaction of year and sowing date affecting maximum LAI in wheat

Treatment	2010-11	2011-12
A) Sowing Date		
SD_1= 15th November	4.73 ab	5.04 a
SD_2= 15th December	3.50 c	4.33 b
LSD 5%	0.53	
Significance	**	

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

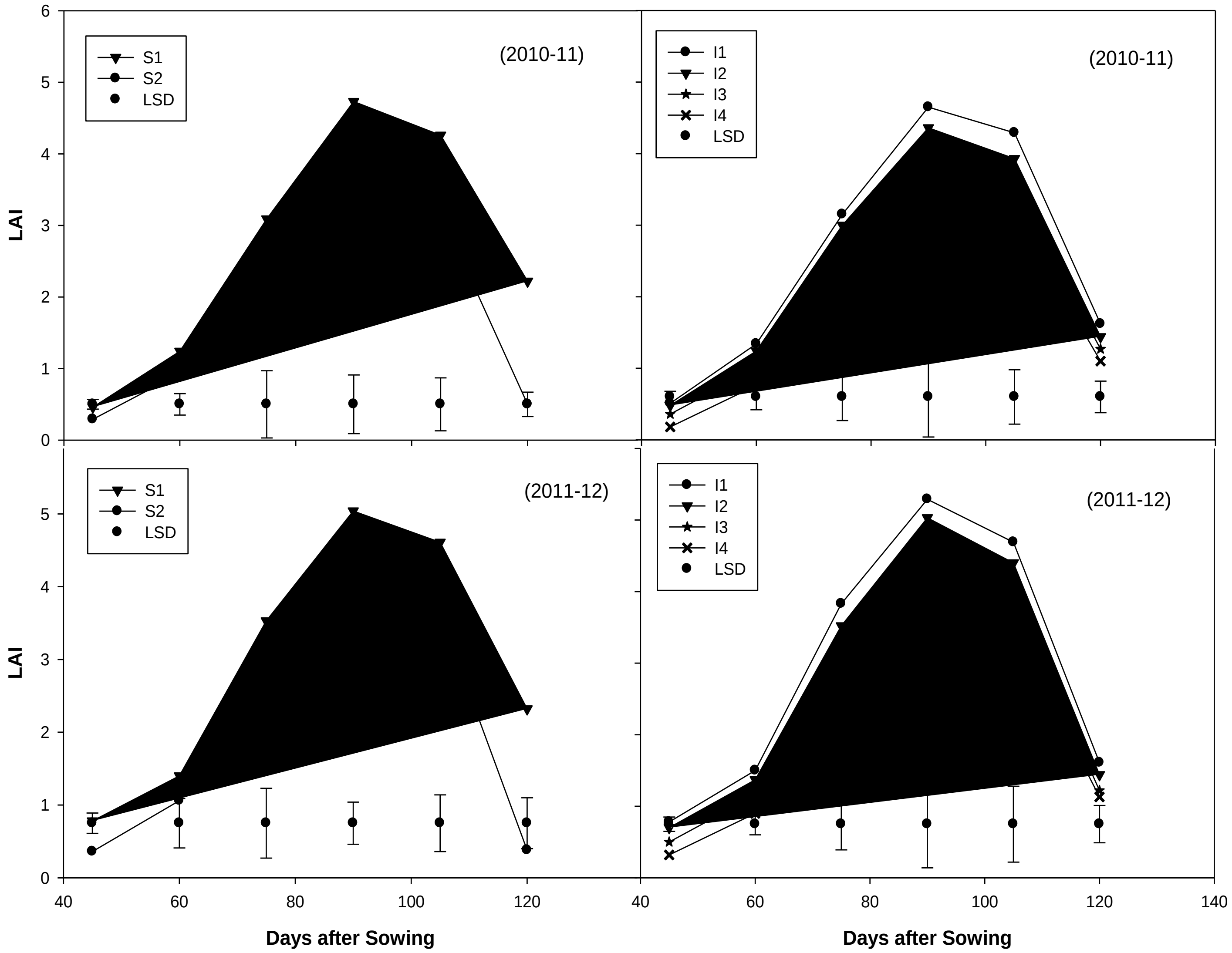


Fig 4.3: Changes in LAI of wheat with time as affected by sowing date and PSMD

Table 4.21: Sowing date and PSMD level affecting TDM (kg ha^{-1}) of wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	10582	11361	10972 a
SD_2= 15th December	8771	9308	9040 b
LSD 5%			398
Significance			**
B) Irrigation			
I_1= Full Irrigation (Control)	11320	11966	11643 a
I_2= 45 mm PSMD	1106	11333	11170 a
I_3= 60 mm PSMD	8796	9683	9239 b
I_4= 75 mm PSMD	7585	8355	7970 c
LSD 5%			684
Significance			**
Interaction			NS
Year Mean	9677	10334	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

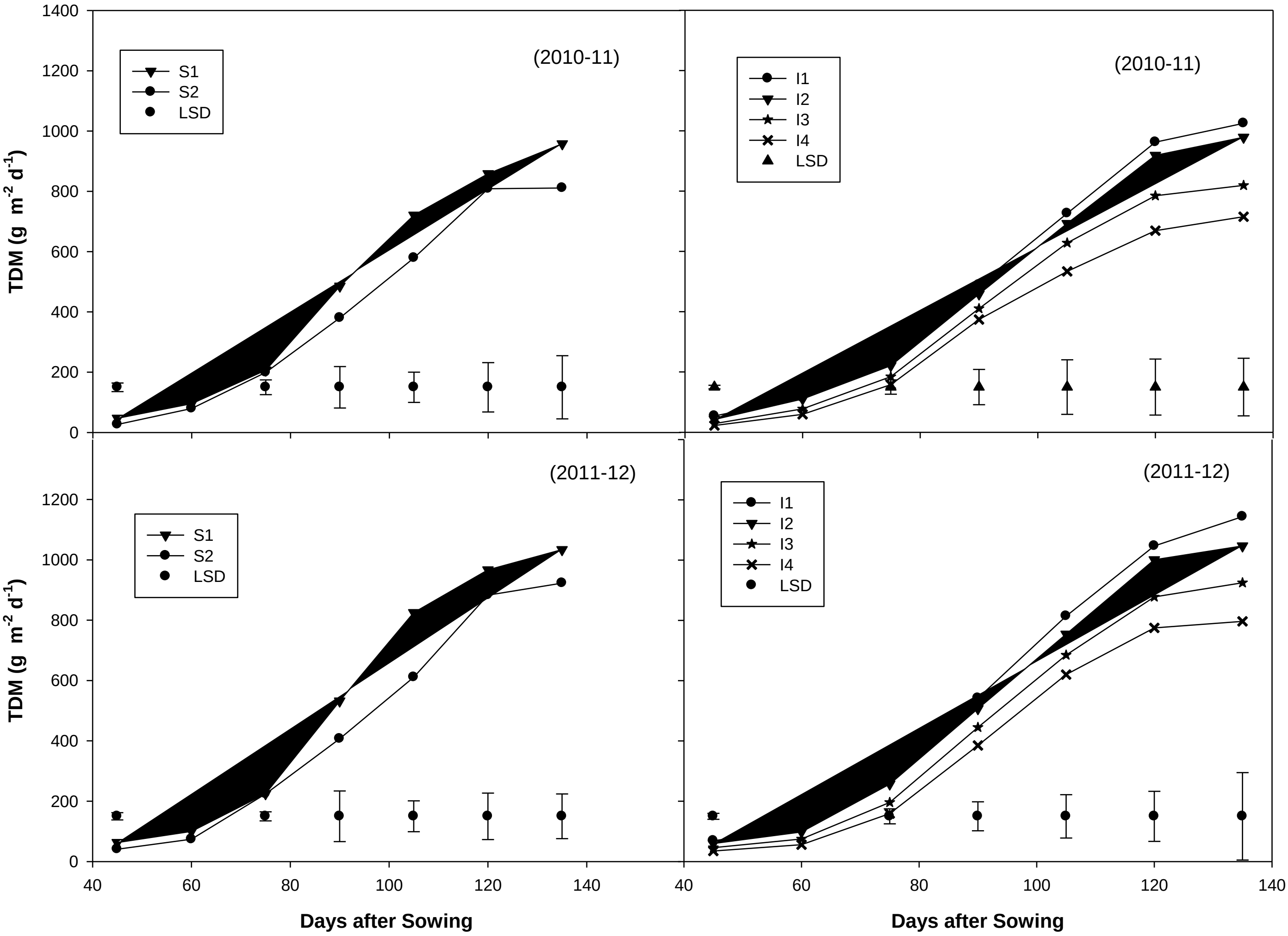


Fig 4.4: TDM accumulation in wheat with time as affected by sowing date and PSMD

assimilating part (leaf area). Year analysis has shown that the biomass production during the both growing season was statistically same.

Total dry matter (TDM) was significantly affected by sowing date (Table 4.21). Planting of wheat on 15th November (SD_1) produced significantly higher grain yield (10972 kg ha^{-1}). Low dry matter was observed on late sowing of wheat (9040 kg ha^{-1}). Decrease in TDM with late sowing is primarily due to low plant density and short growing season length.

Effect of irrigation on TDM was highly significant. Maximum dry matter production of 11643 kg ha^{-1} was recorded in plot receiving full irrigation (I_1). Water stress in I_2 was mild resulting in dry matter statistically similar to fully irrigated plot. Each level of increase in deficit from 45 to 60 and 75 mm PSMD has decreased dry matter significantly and 75 mm PSMD (I_4) has yielded minimum biomass (8355 kg ha^{-1}). Higher deficit level caused low expansion of leaf area which resulted in low interception of solar radiation and its transformation into dry matter.

These results are in conformity with the findings of Shehzad *et al*. (2012) who reported a decrease in biomass with the increase in deficit level from 50 to 75 mm PSMD. Anwar *et al*. (2011) documented that too much early sowing of wheat did not have any positive impact on biomass. They concluded that 20th November is the optimum sowing date for higher biomass and maximum contribution from yield components. Delay in sowing from 20th November to 20th December reduced the biological yield from 13.6 to 9.33 t ha^{-1}.

4.10 ANALYSIS OF GROWTH

4.10.1 Leaf Area Duration (LAD):

Leaf area duration is a measure of persistence of assimilatory surface which is leaf. Data regarding LAD is presented in Table 4.22. As LAD is calculated from LAI, it has the same pattern as that of LAI. Effect of irrigation levels was highly significant in both growing season.

Statistical analysis of year effect has shown that leaf area duration was significantly higher (214 days) in 2011-12 as compared to LAD (189) in 2010-11 (Table 4.22). In 2010-11, significantly higher LAD was recorded with 15th November sowing.

Table 4.22: Sowing date and PSMD level affecting LAD (days) in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	212 a	234 a	223
SD_2= 15th December	166 b	194 b	180
LSD 5%	14	31	
Significance	**	*	
B) Irrigation			
I_1= Full Irrigation (Control)	218 a	248 a	233
I_2= 45 mm PSMD	202 a	231 a	216
I_3= 60 mm PSMD	179 b	203 b	191
I_4= 75 mm PSMD	159 c	173 c	166
LSD 5%	17	18	
Significance	**	**	
Interaction	NS	NS	
Year Mean	189 b	214 a	
LSD 5%	22		
Significance	*		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

Delay in sowing by one month (SD_2= 15th December) has reduced LAD. This reduction is LAD is mainly attributed to shortening of crop growing season length and lower leaf area index throughout the growing season. In 2011-12, delay in sowing has significantly reduced LAD.

In 2010-11, maximum LAD was observed in full irrigation treatment (218) and statistically low LAD (159) was observed in I_4 (75 mm PSMD). In 2011-12, maximum duration for which leaf area remain green was recorded to be 248 in I_1 (Full Irrigation) and statistically lower value was recorded in I_4 (173). During 2011-12, higher LAD was recorded in all the treatment. It was due to reduced lag phase and getting higher LAI at early stage due to comparatively higher temperature at early stage and comparatively lower temperature at flowering stage expand the duration of plant to remain green with higher LAI. Grain yield of wheat is related to post-anthesis leaf area duration. In semi-arid environment, LAD is determined by post anthesis water availability.

4.10.2 Mean Crop Growth Rate:

Seasonal CGR is the average rate of accumulation of dry matter throughout the growing season. It is the product of net assimilation rate and leaf area index. Year analysis showed that rate of dry matter accumulation was statistically same in both growing season (Table 4.23). Analysis of pooled data of both growing season showed that there was a significant decrease in rate of dry matter accumulation from 9.41 to 8.33 g m^{-2} d^{-1} with the delay in sowing from 15th November (SD_1) to 15th December (SD_2).

Fully irrigated plot (I_1) showed maximum rate of crop growth (10.24 g m^{-2} d^{-1}) which was statistically similar to the plot receiving irrigation at 45mm PSMD. Increasing PSMD level from 45 to 75mm significantly decreased crop growth rate.

Dalirie *et al.* (2010) documented slow accumulation of dry matter at early growth stage. Its rate reached to maximum value when plant attained maximum LAI and then it declined due to senescence and reduced leaf area. Guttieri *et al.* (2001) noticed decrease in dry matter accumulation rate due to terminal drought stress which decreased LAI, leaf number and accelerated leaf senescence. Gul *et al.* (2013) reported higher CGR (10.8 and 10.7 g m^{-2} d^{-1}) in wheat crop sown early and on normal time respectively. Growth rate reduced to 6.1 g m^{-2} d^{-1} with delay in planting.

Table 4.23: Sowing date and PSMD level affecting mean CGR (g m^{-2} d^{-1}) in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	9.11	9.71	9.41 a
SD_2= 15th December	7.84	8.81	8.33 b
LSD 5%			0.34
Significance			**
B) Irrigation			
I_1= Full Irrigation (Control)	9.71	10.76	10.24 a
I_2= 45 mm PSMD	9.36	9.87	9.62 a
I_3= 60 mm PSMD	7.9	8.8	8.35 b
I_4= 75 mm PSMD	6.93	7.62	7.28 c
LSD 5%			0.63
Significance			**
Interaction			NS
Year Mean	8.48	9.26	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

4.11 YIELD AND YIELD COMPONENTS

4.11.1 Plant Height:

Plant height is a function of the genetic make up of plant and the environmental conditions prevailing during the growing season. Data regarding the plant height in Table 4.24 show that plant attained statistically similar plant height in response to treatments during both growing season. Delay in sowing by one month from 15th November (SD_1) has significantly decreased plant height from 85.76 cm to 74.64 cm.

Effect of irrigation scheduling based on PSMD on plant height was highly significant. Plot receiving irrigation at Tillering, Stem Elongation, Booting and Grain Formation (I_1) has produced taller plants (84.69 cm). This plot was statistically similar to the plot receiving irrigation at 45 mm PSDM (I_2) which was statistically at par with plot receiving irrigation at 60 mm PSMD (I_3). Plant height was reduced to the least (74.16 cm) in the plot having maximum deficit of water (I_4).

Imam and Segha-Al-Islami (2005) documented that the reduction in plant height is due to reduced carbon dioxide absorption by plant under the circumstances of drought stress. Reduction in turgor pressure of cell is the cause for reduction in plant height (Baroutzadeh *et al.,* 2009). Youssef *et al.* (2013) observed an increase in plant height with the increase in soil moisture (more frequent irrigation). This increase is attributed to the increase in height and/or number of internodes per stem. My results are in in agreement with the findings of Shehzad *et al.* (2012) who reported that plant height was maximum in 50 mm PSMD. Decrease in plant height was recorded by increasing deficit level to 75 mm PSMD. Qasim *et al.* (2008) reported 79.81 cm plant height in plot sown on 15h December. Plant height was decreased as sowing was delayed. They justified the higher plant height with longer vegetative growth period. (Inamullah *et al*., (2007) reported 10.5 to 26% decrease in plant height in late sown crop. Plant stopped its vegetative growth and shifted towards reproductive phase after meeting photoperiodic requirement which resulted in shorter plant height in late sowing. Similar trend was observed by Ahmad *et al.* (2005).

Table 4.24: Sowing date and PSMD level affecting plant height (cm) in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	83.78	87.73	85.76 a
SD_2= 15th December	72.04	77.24	74.64 b
LSD 5%			6.43
Significance			*
B) Irrigation			
I_1= Full Irrigation (Control)	83	86.37	84.69 a
I_2= 45 mm PSMD	81.3	83.9	82.60 ab
I_3= 60 mm PSMD	77.23	81.47	79.35 b
I_4= 75 mm PSMD	70.1	78.21	74.16 c
LSD 5%			4.52
Significance			**
Interaction			NS
Year Mean	77.91	82.49	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

4.11.2 Number of Spikelets per Spike:

Statistical analysis of the year effect showed that plants produced statistically similar number of spikelets per spike (Table 4.25). Sowing date was significantly affected number of spikelets per spike. Higher number of spikelets per spike (15.80) was recorded in plot having sowing date of 15th November (SD_1). Delay in sowing by one month (SD_2) has reduced the number of spikelets per spike to 14.36.

Deficit level significant affected on number of spikelets per spike. Number of spikelets was maximum in fully irrigated plot (I_1). Number of spilelets per spike was started to reduce as the deficit was applied and minimum number of spikelets per spike (14.08) were noticed in plot receiving irrigation at 75mm PSMD (I_4).

Dencic *et al*. (2000) observed that number of spikelets per spike is sensitive to drought stress. Inamullah *et al*. (2007) reported a decrease in number of spikelets per spike with the delay in sowing time.

4.11.3 Grains per spike:

Number of grains set per spike is an important yield contributing component and it depends upon the availability of crop inputs like water and nutrient. Its number is defined before flowering depending upon the crop husbandry. Data regarding number of grains per spike is shown in Table 4.26. From the Table, it is obvious that there was no significant difference in number of grains produced by crop in both growing season. Higher number of grains (34.68) was recorded in 15th November (SD_1) while delay in sowing till 15th December (SD_2) has reduced grain number to 32.99. On an average, delay in sowing by one month reduced the number of grains per spike by 4.87%.

Soil moisture deficit significantly affected on number of grains per spike. Plot receiving full irrigation (I_1) produced maximum number of grains per spike (38.23). Deficit of irrigation (45 mm PSMD) significantly lowered the number of grains per spike and it continued to decrease as potential soil moisture deficit increased.

Table 4.25: Sowing date and PSMD level affecting number of spikelets per spike in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	14.92	16.67	15.80 a
SD_2= 15th December	13.52	15.19	14.36 b
LSD 5%			0.65
Significance			*
B) Irrigation			
I_1= Full Irrigation (Control)	15.58	16.58	16.08 a
I_2= 45 mm PSMD	14.75	16.25	15.50 b
I_3= 60 mm PSMD	13.63	15.63	14.63 c
I_4= 75 mm PSMD	12.9	15.25	14.08 d
LSD 5%			0.53
Significance			**
Interaction			NS
Year Mean	14.22 b	15.93 a	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

Table 4.26: Sowing date and PSMD level affecting number of grains per spike in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	32.93	36.43	34.68 a
SD_2= 15th December	31.53	34.45	32.99 b
LSD 5%			2.21
Significance			*
B) Irrigation			
I_1= Full Irrigation (Control)	37.23	39.23	38.23 a
I_2= 45 mm PSMD	35.53	37.53	36.53 a
I_3= 60 mm PSMD	29.40	33.40	31.40 b
I_4= 75 mm PSMD	26.77	31.60	29.18 b
LSD 5%			3.31
Significance			**
Interaction			NS
Year Mean	32.23	35.44	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

Alignan *et al.* (2009) noted more number of grains per spike in wheat crop sown on conventional sowing date (15th November) and delay in sowing resulted in reduction of grain number per spike. Qasim *et al.* (2008) documented highest grain number in crop sown on 15th November followed by 30th November and then 15th December. Inamullah *et al.* (2007) documented 24.92% reduction in grain number with delay in sowing date. This decrease in grain number with delay in sowing is due to the sensitivity of wheat to photoperiod and temperature (Slafer and Whitechurch, 2001) because ovule is not fertilized properly with the increase in photoperiod and temperature. Shehzad *et al.* (2012) reported maximum number of grains per spike in 50mm PSMD and grain number decreased with the increase in deficit level to 75 mm PSMD. Khan *et al.* 2007 stated that irrigation at five week interval is optimum for getting maximum number of grains per spike. Decreasing irrigation frequency will decrease number of grains per spike due to increased moisture stress.

4.11.4 Productive Tillers (m^{-2}):

Spike bearing tillers at maturity is an important yield determining factor. Data regarding productive tillers in Table 4.27 show that higher number of productive tillers were produced in 2011-12 as compared to 2010-11. It means that differences in weather conditions had significant effect on the productive tillers.

Sowing date has significant impact on number of productive tillers per unit area in both growing season. Higher number of productive tillers was recorded in 15th November sowing (SD_1) and delay in sowing has significantly reduced the number of productive tillers m^{-2}. Similar trend for productive tillers was noticed in second year experiment.

Irrigation levels have shown a significant decrease in productive tillers with increasing water stress level in 2010-11 and highly significant decrease in productive tillers in 2011-12. In 2010-11, 344 tillers m^{-2} were recorded in plot having no water stress (I_1). Performance of this plot was statistically at par with the plot having mild water stress (I_2). Increasing water stress from 45 mm PSMD to 75 mm PSMD has reduced the productive tillers but this reduction was statistically non-significant. In year 2011-12, fully irrigated plot (I_1) produced similar number of grains per spike as recorded in plot receiving irrigation at 45 mm PSMD (I_2) which was at par with 60 mm PSMD (I_3). Minimum number of grains per spike (302) recorded in plot receiving irrigation at 75 mm

Table 4.27: Sowing date and PSMD level affecting productive tillers (m^{-2}) in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	340 a	355 a	348
SD_2= 15th December	292 b	308 b	300
LSD 5%	44	43	
Significance	*	*	
B) Irrigation			
I_1= Full Irrigation (Control)	344 a	365 a	355 a
I_2= 45 mm PSMD	327 ab	341 ab	334 ab
I_3= 60 mm PSMD	304 b	319 bc	312 bc
I_4= 75 mm PSMD	288 b	302 c	295 c
LSD 5%	39	28	
Significance	*	**	
Interaction	NS	NS	
Year Mean	316 b	332 a	
LSD 5%	8		
Significance	*		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

PSMD (I_4) and this plot behaved statistically similar to I_3 for number of productive tillers. In second year trial, subsequent increase in deficit level has reduced the productive tillers.

Similar results were observed by the Khokhar *et al.* (2010) who stated that tillering in wheat was improved by additional irrigation as compared to the single establishment irrigation. Shehzad *et al.* (2012) also proved the same pattern of the productive tillers per unit area in 50 mm PSMD and spike bearing tillers were decreased as deficit was increased to 75 mm PSMD. Khan *et al.* (2007) documented highest number of fertile tillers with more frequent irrigation. Decreasing irrigation frequency will set up high water deficit and reduce number of productive tillers per square meter. Qasim *et al.* (2008) noticed 350 tillers m^{-2} in plot sown on 15th December. Fertile tiller number was reduced as sowing was delayed.

4.11.5 1000-Grain Weight:

Thousand grain weight is determined by the partioning efficiency of assimilates to the economic part of the plant. The difference in thousand grain weight in both growing season was not significant (Table 4.28). Higher thousand grain weight (37.27 g) was recorded in plot sown on 15th December (SD_1). Delay in sowing by one month has significantly reduced the thousand grain weight to 30.86g (- 17.20%). In late sowing date (SD_2), plant was exposed to higher temperature during reproductive phase which shortened its grain growth period and reduced the translocation of dry matter to the economic part of crop.

Effect of irrigation scheduling on thousand grain weight was highly significant. Maximum value of 1000-grain weight (37.46 g) was recorded in plot receiving full irrigation (I_1). Irrigation at 45 mm PSMD (I_2) has resulted in thousand grain weight statistically similar to full irrigation. Grain weight continue to decrease as deficit level was increased and minimum thousand grain weight (33.44 g) was measured in plot having maximum deficit level (I_4) and performance of this plot was statistically similar to I_3.

Trend of my result is in agreement with the findings of Coventry *et al.* (2011) who stated that thousand grain weight will always be lower in late sown crop and first sowing date has highest thousand grain weight. Shehzad *et al.* (2012) reported higher grain weight in 50 mm PSMD and it decreased with the increase of deficit level to 75 mm

Table 4.28: Sowing date and PSMD level affecting thousand grain weight (g) in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	35.30	39.23	37.27 a
SD_2= 15th December	30.11	31.60	30.86 b
LSD 5%			3.76
Significance			*
B) Irrigation			
I_1= Full Irrigation (Control)	36.09	38.82	37.46 a
I_2= 45 mm PSMD	34.27	36.50	35.39 ab
I_3= 60 mm PSMD	31.54	34.37	32.96 bc
I_4= 75 mm PSMD	28.90	31.97	30.44 c
LSD 5%			2.69
Significance			**
Interaction			NS
Year Mean	32.70	35.42	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

PSMD. Similar was the pattern of thousand grain weight for deficit irrigation in my study. Qasim *et al.* (2008) recorded higher 1000-grain weight (39.17 g) in crop sown on 15th November and it was decreased to 30.71 g when sowing was delayed to 15th December. In delayed sowing, shortening of each growing stage, particularly grain formation is the main reasonfor lower grain weight. Inamullah *et al.* (2007) noted 19.72% decrease in grain weight due to delay in sowing of wheat because plant does not have sufficient time to increase grain weight due to shorter photoperiod and higher temperature (Slafer and Whitechurch, 2001).

4.11.6 Grain Yield:

Grain yield is interplay of its contributing components which are spike bearing tillers, average number of grain on spike and mean grain weight. Changes in any of these associated components will lead to change in grain yield. Year effect was found to be significant with higher grain yield in 2011-12 due to significantly higher number of productive tillers in that year (Table 4.29). Each treatment performed comparatively better in 2011-12 as compared to 2010-11 due to more favorable climatic conditions, longer growing season resulting in interception of more solar radiation and its transformation into dry matter.

Effect of sowing date on grain yield was significant in both growing season. Higher yield was recorded in 15th November sowing (SD_1). Grain yield was decreased by 23.72 % and 24.87 % due to delay in sowing by one month on 2010-11 and 2011-12 respectively. Shorter growing season length, less interception of PAR and exposure to high temperature particularly during grain formation finally leads to less biomass production at late sown crop. Low dry matter accumulation and reduced efficiency to convert it into the economical part is the main reason of low grain yield in late sowing date.

The effect of deficit irrigation on grain yield was highly significant during both growing season. Highest grain yield (3833 kg ha^{-1}) was recorded in full irrigation treatment which was statistically at par with I_2 (3355 kg ha^{-1}). Increasing deficit level has significantly decreased grain yield. Minimum grain yield was found in I_4 (2027 kg ha^{-1}). A similar trend of decrease in grain yield with the increasing stress level was noticed in 2011-12.

Table 4.29: Sowing date and PSMD level affecting grain yield (kg ha^{-1}) in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	3364 a	3856 a	3610
SD_2= 15th December	2566 b	2897 b	2731
LSD 5%	461	608	
Significance	*	*	
B) Irrigation			
I_1= Full Irrigation (Control)	3833 a	4249 a	4040
I_2= 45 mm PSMD	3355 a	3882 a	3618
I_3= 60 mm PSMD	2645 b	3008 b	2826
I_4= 75 mm PSMD	2027 c	2367 c	2196
LSD 5%	478	472	
Significance	**	**	
Interaction	NS	NS	
Year Mean	2965 b	3376 a	
LSD 5%	407		
Significance	*		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

Alignan *et al*. (2009) also cited that there were significant differences among all the traits between two sowing dates. Yield contributing factors (productive tillers m^{-2}, number of grains per spike and 1000 grains per spike) were decreased due to late sowing (Asseng and Milory, 2006; Spiertz *et al*., 2006). This decrease in grain yield can be related to the differences in weather conditions prevailing throughout the growing season particularly during grain formation (Xu *et al*., 2007; Coventry *et al*., 2011). Higher temperature and terminal drought were pronounced in delayed sowing date. Early sowing benefits the crop due to early flowering and long maturation time. Tripathi *et al*. (2005) reported reduction in wheat yield (32 kg ha^{-1} day^{-1}) with delay in sowing time from first fortnight of November to first fortnight of December. But this decrease of yield is not uniform with the change in sowing date. Malik *et al.* (2007) reported yield reduction of 8.85 kg ha^{-1} day^{-1} and 30.11 kg ha^{-1} day^{-1} with second fortnight of November and December. Hussain *et al*. (2004) suggested increase in grain yield by promoting early leaf expansion which is more likely to occur in early sown crop as compared to late sown crop. Qasim *et al.* (2008) reported decrease in grain yield by 45.19% as sowing was delayed from 15^{th} November to 15^{th} December. Inamullah *et al.* (2007) reported maximum grain yield of 4456 kg ha^{-1} in early sown wheat crop and there was significant reduction in yield as sowing was delayed. Decrease in grain yield in late sown crop is due to reduced growing degree days, longer photoperiod and higher temperature during reproductive stage (Slafer and Whitechurch, 2001). Similarly Ali *et al.* (2004) reported higher grain yield in wheat crop sown on 10^{th} November and yield decreased by 33.86% as planting date was shifted towards 30^{th} December. Khan *et al.* (2007) also supported the idea that too early and too late irrigation decrease the grain yield due to moisture stress.

4.11.7 Harvest Index:

Harvest Index (HI) is the efficiency of the cultivar to translocate assimilates in economically important part of crop. Data regarding the effect of sowing date and irrigation is shown in Table 4.30. Year analysis showed that HI during both years was statistically similar. Harvest index was significantly affected by sowing dates and deficit levels. Interactive effect of irrigation and sowing date shows that partitioning efficiency of dry matter into economical part was maximum in fully irrigated plot and plot irrigated at 45 mm PSMD in 15^{th} November sowing date (SD_1) (Table 4.31). Harvest index of SD_1 X I_2 was statistically at par with 60 mm PSMD in 15^{th} November sowing and fully irrigated plot (I_1) and 45 mm PSMD (I_2) in 15^{th} December sowing (SD_2). HI decreased

Table 4.30: Sowing date and PSMD level affecting harvest index (%) in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	31.35	33.56	32.46 a
SD_2= 15th December	28.97	30.88	29.93 b
LSD 5%			1.60
Significance			**
B) Irrigation			
I_1= Full Irrigation (Control)	33.71	35.40	34.56 a
I_2= 45 mm PSMD	30.27	34.22	32.25 b
I_3= 60 mm PSMD	29.70	30.83	30.27 c
I_4= 75 mm PSMD	26.96	28.43	27.70 d
LSD 5%			1.59
Significance			**
Interaction			*
Year Mean	28.17	30.42	
LSD 5%			
Significance	NS		

Table 4.31: Interactive effect of sowing date and PSMD level affecting harvest index (%) in wheat

Treatment	SD_2= 15th November	SD_2= 15th December
Irrigation		
I_1= Full Irrigation (Control)	35.99 a	33.12 bc
I_2= 45 mm PSMD	34.12 ab	30.36 cd
I_3= 60 mm PSMD	32.77 bc	27.76 de
I_4= 75 mm PSMD	26.93 e	28.46 de
LSD 5%	2.99	
Significance	*	

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

with the increase in deficit level and delay in sowing. Minimum harvest index was recorded in 75 mm PSMD at 15th November sowing and 60 and 75 mm PSMD at 15th December sowing. Higher temperature at reproductive stage reduced the plant ability to mobilize assimilates towards the grain (4.11.7b).

Shehzad *et al*. (2012) reported maximum efficiency to convert dry matter into grain yield in plot irrigated at 50 mm PSMD. Increasing deficit level to 75 mm PSMD decreased HI. Similar was the pattern observed in my study.

4.12 GRAIN GROWTH

Rate of grain growth was statistically similar in both growing seasons (Table 4.32). Rate of dry matter accumulation in grain was higher (1.43 mg day^{-1}) in 15th November sowing date (SD_1) as compared to the grain growth rate (1.15 mg day^{-1}) in late sown (SD_2) wheat. Irrigation scheduling significantly affected grain growth rate. Higher grain growth rate (1.35 mg day^{-1}) was recorded in fully irrigated plot (I_1) and it was statistically at par with the grain growth plot irrigated at 45 mm PSMD (I_2). Grain growth rate was decreased with the increase in potential soil moisture deficit level and reached its minimum rate (1.14 mg day^{-1}) in plot irrigated at 75 mm PSMD (I_4). This plot was statistically at par with plot irrigated at 60 mm PSMD (I_3) which showed the daily accumulation of 1.20 g dry matter in grain from anthesis to physiological maturity. Fig4.5 shows the daily accumulation of photosynthates into grain during grain development. At early stage of grain development, photosynthate accumulation was low, then it increased with the passage of time. The rate of grain growth dropped down as cop completed its life cycle and reached physiological maturity.

Table 4.32: Sowing date and PSMD level affecting rate of grain growth (mg day^{-1}) in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	1.27	1.40	1.34 a
SD_2= 15th December	1.11	1.18	1.15 b
LSD 5%			0.12
Significance			*
B) Irrigation			
I_1= Full Irrigation (Control)	1.29	1.40	1.35 a
I_2= 45 mm PSMD	1.22	1.32	1.27 ab
I_3= 60 mm PSMD	1.15	1.25	1.20 bc
I_4= 75 mm PSMD	1.10	1.17	1.14 c
LSD 5%			0.11
Significance			**
Interaction			NS
Year Mean	1.19	1.29	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

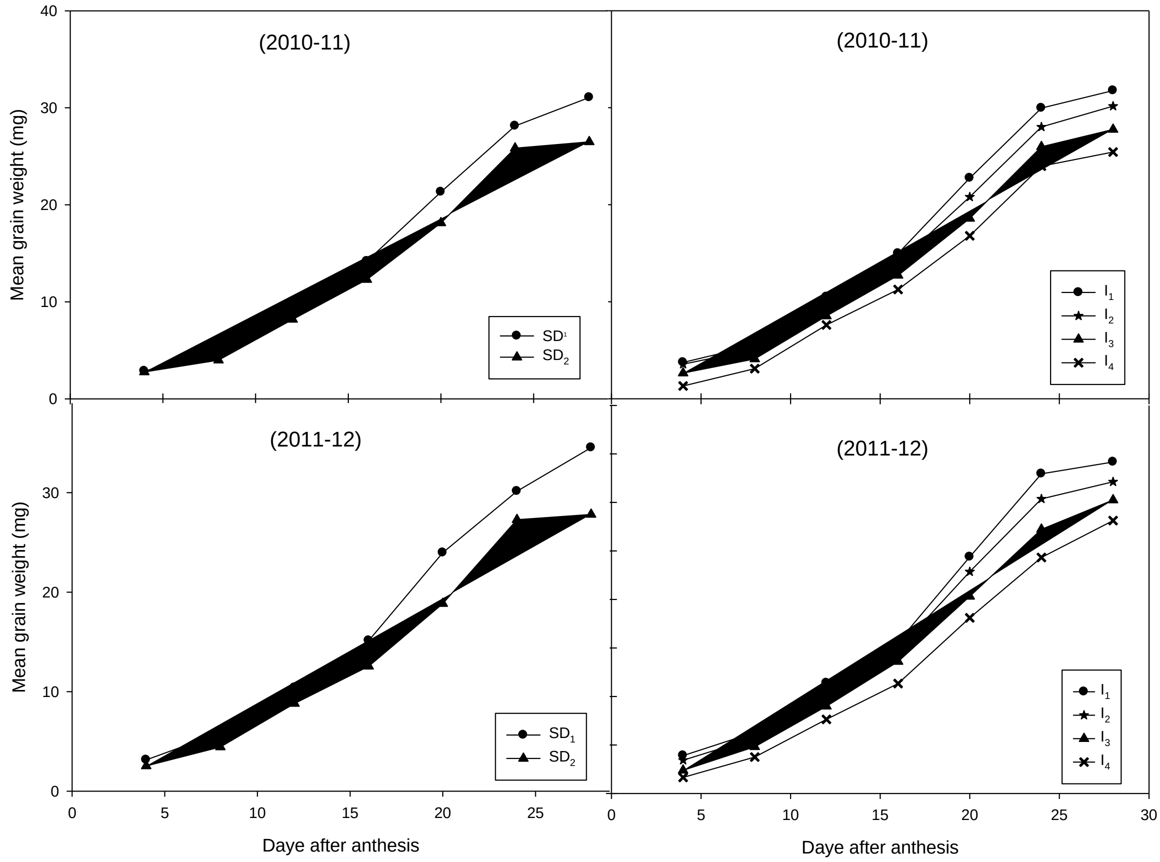


Fig 4.5: Grain growth of wheat after anthesis as affected by sowing date and potential soil moisture deficit in 2010-11 and 2011-12.

4.13 RADIATION USE EFFICIENCY

4.13.1 Cumulative Intercepted PAR:

More PAR was intercepted (455 MJ m^{-2}) by the crop throughout the growing season in 2011-12 as compared to PAR intercepted (404 MJ m^{-2}) during the season of 2010-11 (Table 4.33). As there were significant differences in interception of PAR, it would be discussed for both years separately. Values in parenthesis showed the total PAR available throughout the growing season. Effect of sowing date on cumulative interception of PAR was significant in both growing season. In 2010-11, crop sown on 15^{th} November (SD_1) intercepted 415 MJ m^{-2} of PAR while the total PAR available during the season was 1016 MJ m^{-2}. Crop utilized only a part of available PAR due to less interception capacity. One month delay in sowing (SD_2) reduced the amount of PAR intercepted by crop (392 MJ m^{-2}). Low interception of PAR was the result of less availability of PAR (921 MJ m^{-2}) and its less interception due to lower leaf area index throughout the growing season. Similar trend of PAR interception by crop for sowing date was recorded in 2011-12. Photosynthetically active radiation to the plant was 1115 and 1039 MJ m^{-2} and its interception was 475 and 435 MJ m^{-2} for SD_1 and SD_2 respectively. Less interception of PAR in late sowing is due to lower maximum LAI and its lesser tendency to remain green for long time (LAD).

Irrigation has highly significant effect on intercepted PAR for both years. During 2010-11, higher interception of PAR (446 MJ m^{-2}) was calculated with Full Irrigation (I_1) and it was statistically at par with I_2 (422 MJ m^{-2}). Light interception decreased significantly with increasing deficit level. Statistically low interception of PAR (352 MJ m^{-2}) was recorded with I_4 (Irrigation at 75mm PSMD). Same trend was observed in 2011-12 with maximum but statistically at par Intercepted photosynthetically active radiation was recorded with I_1 (503 MJ m^{-2}) and I_2 (479 MJ m^{-2}) treatments and statistically lower PAR was recorded with I_4 (390 MJ m^{-2}). Incident PAR was same in all the treatments, it was the LAI which determine proportion of incident PAR to be intercepted. Tariq *et al.* (2012) also stated a direct and linear relationship between biomass and intercepted PAR.

Table 4.33: Sowing date and PSMD level affecting cumulative intercepted PAR (MJ m^{-2}) in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	415 a (1016)	475 a (1115)	443
SD_2= 15th December	392 b (921)	435 a (1039)	409
LSD 5%	17	38	
Significance	*	*	
B) Irrigation			
I_1= Full Irrigation (Control)	446 a	506 a	475
I_2= 45 mm PSMD	426 a	482 a	454
I_3= 60 mm PSMD	391 b	437 b	414
I_4= 75 mm PSMD	352 c	395 c	374
LSD 5%	21	31	
Significance	**	**	
Interaction	NS	NS	
Year Mean	404 b	455 a	
LSD 5%	47		
Significance	*		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

4.13.2 RUE for Grain Yield:

Radiation use efficiency is the dry matter produced by utilizing a unit of intercepted photosynthetic active radiation. Statistical analysis shows that conversion of intercepted PAR into grain was same in both growing season (Table 4.34). Radiation use efficiency for grain yield was highly significantly affected by sowing date. 0.80 g grain biomass was produced by utilizing one unit of PAR in unit area with the crop sown on 15^{th} November (SD_1). Grain biomass production was significantly reduced to 0.65 g for the same amount of PAR in the plot sown on 15^{th} December (SD_2).

Impact of irrigation scheduling on radiation use efficiency for grain yield was also highly significant. Efficiency of conversion of a unit of intercepted PAR into grain yield was maximum in fully irrigated plot (I_1) and plot receiving irrigation at 45 mm PSMD (I_2). These both plot produced 0.82 and 0.79 g of grain yield per mega Joule of light in one square meter area. This efficiency of conversion of intercepted PAR into grain yield decreased as the deficit level was increased from 45 to 75 mm PSMD.

These results are in agreement with the Shehzad *et al.* (2012) who reported maximum RUE in 50 mm PSMD and it decreased with the increase in water stress. Hussain *et al.* (2004) observed a strong negative relationship between RUE and PSMD. They observed reduction in RUE from 7.02 to 46.12% with the increase in deficit level as compared to fully irrigated treatment. In another year, when high rainfall was reported, they observed 4.21 to 15.54% reduction in RUE with irrigation stress treatments.

4.13.3 RUE for TDM:

Efficiency of conversion of intercepted PAR into total dry matter was statistically same during both growing season (Table 4.35). Effect of sowing date on RUE for TDM was highly significantly. 2.46 g of total dry matter was produced by utilizing one mega joule of intercepted PAR in unit area in plot sown on 15^{th} November (SD_1). Efficiency of conversion of intercepted PAR into TDM was reduced to 2.17 g m^{-2} MJ^{-1} in plot having sowing date of 15^{th} December (SD_2). In delayed sowing, interception of PAR was less and conversion efficiency into dry matter decreased possibly due to exposure to high temperature at the later stage.

Table 4.34: Sowing date and PSMD level affecting RUE for grain yield ($g\ m^{-2}\ MJ^{-1}$) in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	0.80	0.80	0.80 a
SD_2= 15th December	0.65	0.66	0.65 b
LSD 5%			0.01
Significance			**
B) Irrigation			
I_1= Full Irrigation (Control)	0.86	0.84	0.82 a
I_2= 45 mm PSMD	0.79	0.8	0.79 a
I_3= 60 mm PSMD	0.68	0.69	0.68 b
I_4= 75 mm PSMD	0.57	0.59	0.58 c
LSD 5%			0.06
Significance			**
Interaction			NS
Year Mean	0.72	0.73	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

Table 4.35: Sowing date and PSMD level affecting RUE for TDM (g m^{-2} MJ^{-1}) in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	2.54	2.39	2.46 a
SD_2= 15th December	2.21	2.12	2.17 b
LSD 5%			0.05
Significance			**
B) Irrigation			
I_1= Full Irrigation (Control)	2.53	2.36	2.44 a
I_2= 45 mm PSMD	2.58	2.35	2.46 a
I_3= 60 mm PSMD	2.25	2.22	2.23 b
I_4= 75 mm PSMD	2.14	2.1	2.12 c
LSD 5%			0.11
Significance			**
Interaction			NS
Year Mean	2.38	2.26	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

Impact of irrigation scheduling was highly significantly on the efficiency of utilization of photosynthetically active radiation. High RUE of 2.44 and 2.46 g m^{-2} MJ^{-1} was recorded in fully irrigated plot (I^1) and plot irrigated at 45 mm PSMD (I_2). Efficiency of utilization of PAR into TDM was reduced significantly with the each level of increase in potential soil moisture deficit level. Radiation use efficiency was decreased to 2.23 g m^{-2} MJ^{-1} with plot receiving irrigation at 60 mm PSMD. Minimum RUE (2.12 g m^{-2} MJ^{-1}) was calculated in the plot receiving irrigation at 75 mm PSMD. Similar are the results documented by Shehzad *et al*. (2012).

4.14 WATER USE EFFICIENCY

Statistical analysis showed that crop has produced the same amount of grain yield by evapo-transpiring one millimeter of water (Table 4.36). Sowing date has highly significant impact on water use efficiency. 2.17 g of grain biomass was produced in unit area by losing one millimeter of water in the form of evaporation cum transpiration in plot sown on 15^{th} November (SD_1). But this efficiency of grain yield production for same amount of water was reduced to 1.68 g m^{-2} mm^{-1} in the plot sown on 15^{th} December (SD_2).

Impact of irrigation scheduling on WUE was highly significant. Maximum water use efficiency of 2.22 g m^{-2} mm^{-1} was recorded in fully irrigated treatment. Performance of this plot was statistically similar to the treatment having a deficit level of 45 mm PSMD (I_2). Amount of water applied in I_2 was less as compared to I_1, but the efficiency of grain biomass production was statistically same in both plots. Higher deficit levels of 60 and 75 mm PSMD has reduced the water use efficiency to 1.80 and 1.55 g m^{-2} mm^{-1} respectively. It means that plant has crossed its minimum allowable deficit level and it has highly significantly reduced the grain yield per unit of water lost in evaporation and transpiration.

Table 4.36: Sowing date and PSMD level affecting WUE (g m^{-2} mm^{-1}) based on crop ET in wheat

Treatment	2010-11	2011-12	Mean
A) Sowing Date			
SD_1= 15th November	2.13	2.21	2.17 a
SD_2= 15th December	1.66	1.71	1.68 b
LSD 5%			0.09
Significance			**
B) Irrigation			
I_1= Full Irrigation (Control)	2.22	2.22	2.22 a
I_2= 45 mm PSMD	2.07	2.17	2.12 a
I_3= 60 mm PSMD	1.78	1.83	1.80 b
I_4= 75 mm PSMD	1.51	1.61	1.55 c
LSD 5%			0.14
Significance			**
Interaction			NS
Year Mean	1.89	1.96	
LSD 5%			
Significance	NS		

Figures having different letters in a column differ significantly at $P \leq 0.05$

*, ** = Significant at 5% and 1%, respectively, NS = Non-significant

PSMD = Potential Soil Moisture Deficit

4.15 CROP MODELING

4.15. 1 Model Calibration

CERES-Wheat Model was calibrated with full irrigation (I_1= Irrigation at Tillering, Stem Elongation, Booting and Grain Formation) and non-stress fertilizer (F_3= 160 kg N ha^{-1}) during year 2011-12. CERES-Wheat model simulated phenology, growth and yield by using seven genetic coefficients in Cultivar file (Table 4.37). The Value of the vernalizing temperature requirement (P1V) was 5 days showing that it has little or no vernalizing requirement and Photo period response (P1D) was 103. Grain filling duration (P5) was 484 ^oC days. G1 (Kernel number per unit canopy weight at Anthesis) was 20 and G2 (Standard kernel size under optimum conditions) was found to be 28 mg. Weight of the non-stress mature tiller (G3) was 1.0. Interval of 120 ^oC days was found between successive leaf tip appearances (PHINT). Same genetic coefficients were used for model evaluation and validation in Experiment I and Experiment II.

Calibration of CERES-Wheat Model shows that model performed well in simulating phenology, growth and yield of Wheat (Table 4.38). The difference in simulated and observed values of days to Anthesis was 2 days with an error of -1.75%. Model simulated equal number of days to maturity as measured in field experiment (0% error). Model simulated the grain yield (4789 kg ha^{-1}) very much closed to observed value with a minute error of 0.44%. Fig 4.15 shows that there was a good deed of agreement between observed and simulated LAI (R^2=0.80, d-stat= 0.94) with an error of 0.88. At early growth stages, model slightly under estimated LAI. At 90 days after sowing, plant attained its maximum LAI. After that there is gradual decrease in LAI but model simulated that LAI was sustained for a time and there was drop down in LAI. TDM accumulation with time was in a strong agreement (R^2=0.99, d-stat= 0.99) with the simulated TDM. Overall error in simulating TDM was low (RMSE= 506 kg ha^{-1}).

CERES-Wheat model calibration showed satisfactory estimates for anthesis and physiological maturity date (Singh *et al.*, 2008). Simulation for grain yield was also very close to the observed value. However accuracy of model for simulating biomass and LAI was poor.

Table 4.37: Genetic coefficient for CERES-Wheat Model

Cultivar	P1V	P1D	P5	G1	G2	G3	PHINT
SAHAR-2006	5	103	484	20	28	1.0	120

P1V= Days, optimum vernalizing temperature, required for vernalization
P1D= Photoperiod response (% reduction in rate/10 h drop in pp)
P5= Grain filling (excluding lag) phase duration ($^oC.d$)
G1= Kernel number per unit canopy weight at anthesis (#/g)
G2= Standard kernel size under optimum conditions (mg)
G3= Standard, non-stressed mature tiller wt (incl grain) (g dwt)
PHINT= Interval between successive leaf tip appearances ($^oC.d$)

Table 4.38: Observed and simulated results during model calibration (I_1F_3) from Experiment I data during 2011-12.

Variable	Unit	Obs	Sim	Error (%)
Anthesis	Day	116	114	-1.75
Maturity	Day	144	144	0.00
Grain Yield	kg ha^{-1}	4810	4789	-0.44
Biomass	kg ha^{-1}	12889	12681	-1.64

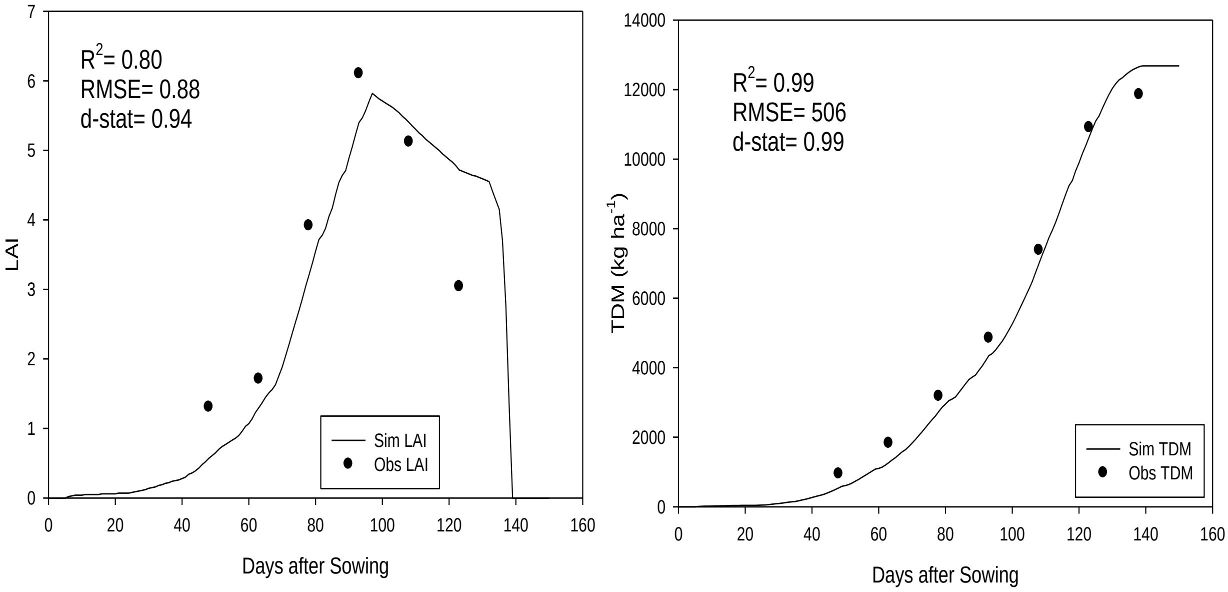


Fig 4.6: Time course changes in Observed and Simulated LAI and TDM for calibration treatment (I_1F_3).

4.15.2 Model Evaluation and Validation:

Model was run with the same experiment in year 2011-12, excluding calibration treatment, with the same genetic coefficients to check the performance of coefficients and accuracy of model simulation for evaluation. Independent data set of the same experiment in year 2010-11 was used for model validation. Simulation outcomes from the CERES-Wheat Model are described below. Kaur *et al.* (2007) found a root mean square error of 6.2 to 6.9 with R^2 of 0.79 to 0.94 for days to anthesis and physiological maturity respectively. But the prediction of biomass was poor (RMSE= 1520 kg ha^{-1}). In another simulation study conducted by Saseendran *et al*. (2004) found that anthesis and flowering days were simulated within the range of -6 to +2 days and -4 to +1 days respectively.

4.15.2.1 Grain Yield:

Fig 4.7 shows 1:1 line graph for comparison between observed and simulated values of grain yield for Model evaluation (2011-12) and validation (2010-11). Model evaluation shows that model precisely simulated the grain yield for all the treatments (excluding calibration treatment). Coefficient of determination (R^2= 0.72) shows that simulated values of model followed the same pattern as recorded in field experiment with a strong agreement (d-stat= 0.90). grain yield for some treatment was slightly under estimated and for rest of the treatments, it was over estimated but average error for simulating grain yield for all the treatments was quite low (RSME= 446 kg ha^{-1}). Accuracy for simulating grain yield during model validation was quite higher as supported by good statistical indices (R^2= 0.80, d-stat= 0.93). Some points fall on 1:1 line showing that these treatments have exactly similar observed and simulated grain yield. Grain yield of three treatments was slightly under estimated and rest of the treatments was over estimated by the model but they were also close to the measured data. Root mean square error for grain yield was low (359 kg ha^{-1}). Over all, performance of CERES-Wheat model was good with an accuracy of more than 90% in simulating grain yield for different irrigation and fertilizer levels.

Same trend of grain yield simulation was recorded for Experiment II. Differences were very small between simulated and observed grain yield for different irrigation levels

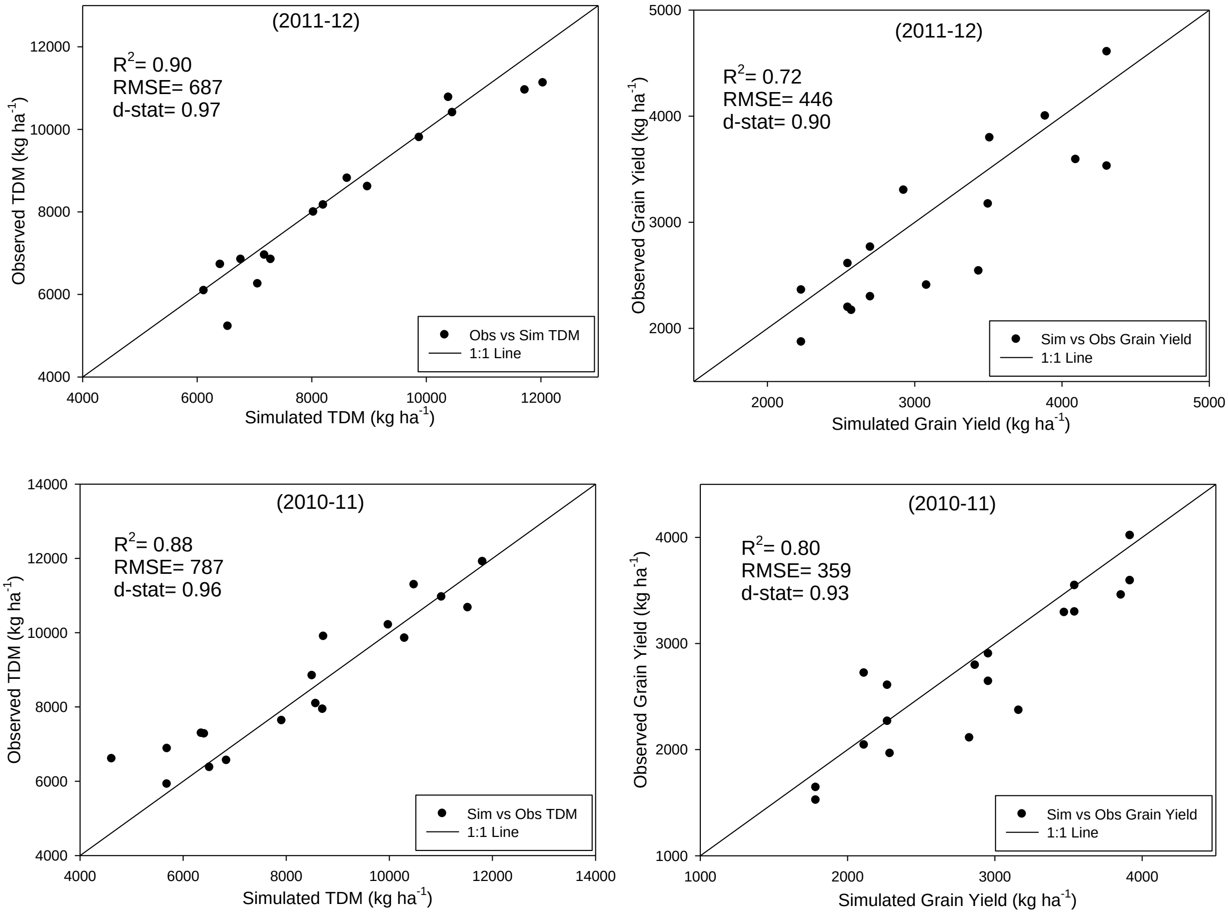


Fig 4.7: Comparison between simulated and observed Grain yield and Biological Yield for Model Evaluation and Validation for Experiment-I.

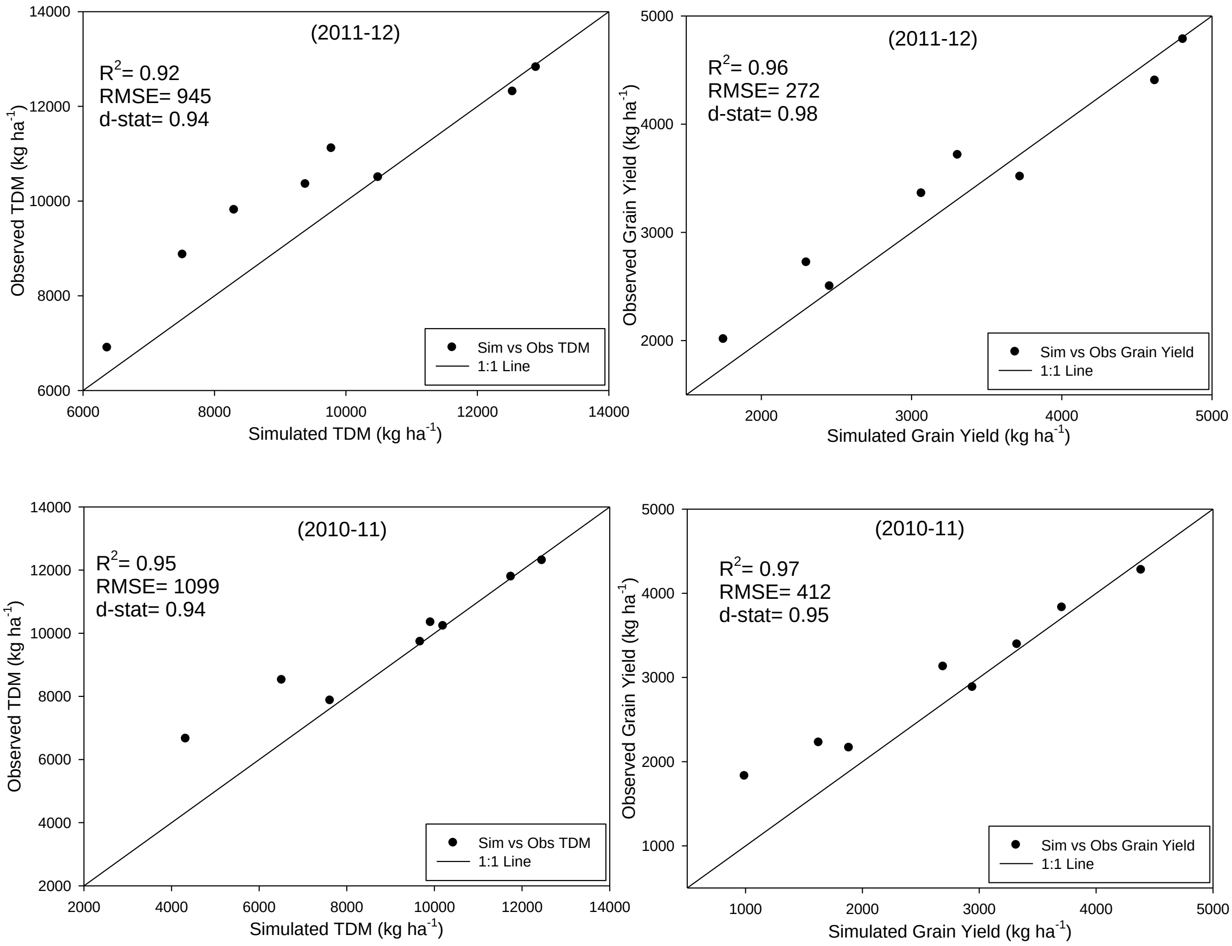


Fig 4.8: Comparison between simulated and observed Grain yield and Biological Yield for Model Evaluation and Validation for Experiment-II.

based on potential soil moisture deficit and sowing dates (Fig 4.15.3). Small root mean square error (272 kg ha^{-1}) was recorded for model evaluation and error during model validation was 412 kg ha^{-1}. Regression coefficient (0.96 and 0.97) and d-stat (0.98 and 0.95) were quite high for model evaluation and validation showing a strong agreement between simulated and observed grain yield. Overall CERES-Wheat model performed well ti simulate grain yield for different agro-management practices.

Singh *et al*. (2008) observed the simulated response of grain yield to nitrogen levels upto 90 kg ha^{-1} during model evaluation. Beyond that level, increase in simulated grain yield was very low. Simulated yield of fully irrigated crop fit best with the observed value as compared to drought stress treatment. In drought stressed treatment, error percentage ranged from 0.62 to 9.80% with RSME of 630 kg ha^{-1}. Heng *et al*. (2001) also reported good agreement between observed and simulated biomass by CERES-Wheat model. Saseendran *et al*. (2004) validated the CERES-Wheat model and found a good agreement between simulated and observed grain yield.

4.15.2.2 Total Dry Matter (TDM):

Fig 4.8 is the graphical representation of simulated and observed biomass for model evaluation (2011-12) and validation (2010-11). Model performance for simulation of biomass during evaluation was good because simulated values for different treatments were very close biomass to observed values. Coefficient of determination and d-stat were very high (0.90 and 0.97 respectively) and error was quite low (RMSE= 687 kg ha^{-1}). Model validation results show that model simulated the same trend for different treatments as recorded in field experiment (R^2= 0.88, d-stat= 0.96). Over all error in forecasting biomass was less than 10% (RMSE= 787 kg ha^{-1}).

Model simulation for biomass at various irrigation levels based on PSMD and sowing dates (Exp II) was also well as supported by high value of R^2 (0.92 and 0.95) and d-stat (0.94 and 0.94) for model evaluation and validation, respectively (Fig 4.8). But root mean square error was measured to be 945 kg ha^{-1} and 1099 kg ha^{-1} for year 2011-12 and 2010-11 respectively.

Singh *et al*. (2008) documented that CERES-Wheat under estimate the biomass for different irrigation regimes and nitrogen level. Deviation of simulated biomass for different irrigation schedule varies from 0.06 to 40.0% from observed value. But the coefficient of determination was very high (0.98). Heng *et al*. (2001) also reported good agreement between observed and simulated biomass by CERES-Wheat. Bannayan *et al*. (2003) reported large error for simulated biomass production due to the lack of ability of the model to develop the link between biomass and yield. Model simulated biomass well for nitrogen application rates with RMSE= 1247 kg ha^{-1}. (Saseendran *et al*., 2004).

4.16 CLIMATE CHANGE SCENARIOS GENERATION

To generate climate change scenarios under semi-arid conditions of Faisalabad, twenty GCMs with RCP 4.5 were used for Baseline (1980-2010). Climate scenarios were generated for Mid-century (2040-2069) and End of century (2070-2099) using R-scripts. Each GCM simulated daily weather data for thirty years. All the GCMs showed increase in seasonal average temperature as compared to baseline (17.85 ^{o}C) in Mid-century ranging from 17.70 ^{o}C (INM-CM4) to 22.10 ^{o}C (MIROC-ESM). There is a lot of variability in rainfall as compared to seasonal average rain in baseline (82.91 mm). Seasonal average rainfall may decrease upto 50.53 mm (according to MPI-ESM-LR) and it can increase upto 163.61 mm (IPSL-CM5A-LR).

In End of Century (2070-2099), temperature rise is expected to range from 19.44 ^{o}C (INM-CM4) to 23.05 ^{o}C (MIROC-ESM). Variability in precipitation will range from 53.34 mm (MPI-ESM-LR) to 159.83 mm (IPSL-CM5A-LR).

Out of these 20 GCMs, 5 GCMs were selected based on variability in temperature and precipitation. Selected one GCM (K) have higher rain fall during the season as compared to baseline and other four GCMs (GFDL-ESM2M, CCSM4, MPI-ESM-LR, MIROC5) have low rainfall but all GCMs show rise in temperature as compared to baseline both for Mid and End Century (Fig 4.11).

Villegas and Challinor (2012) concluded that GCMs can be used with a certain degree of confidence for some areas and time periods. Model can be bias corrected for the areas which lack enough skill for modeling (Challinor *et al*., 2009) because development of adaptation strategy requires proper projection of climate change scenarios. Asseng *et al*. (2013) also used the general circulation models to generate the future weather data and assess the variability in extent of climate change.

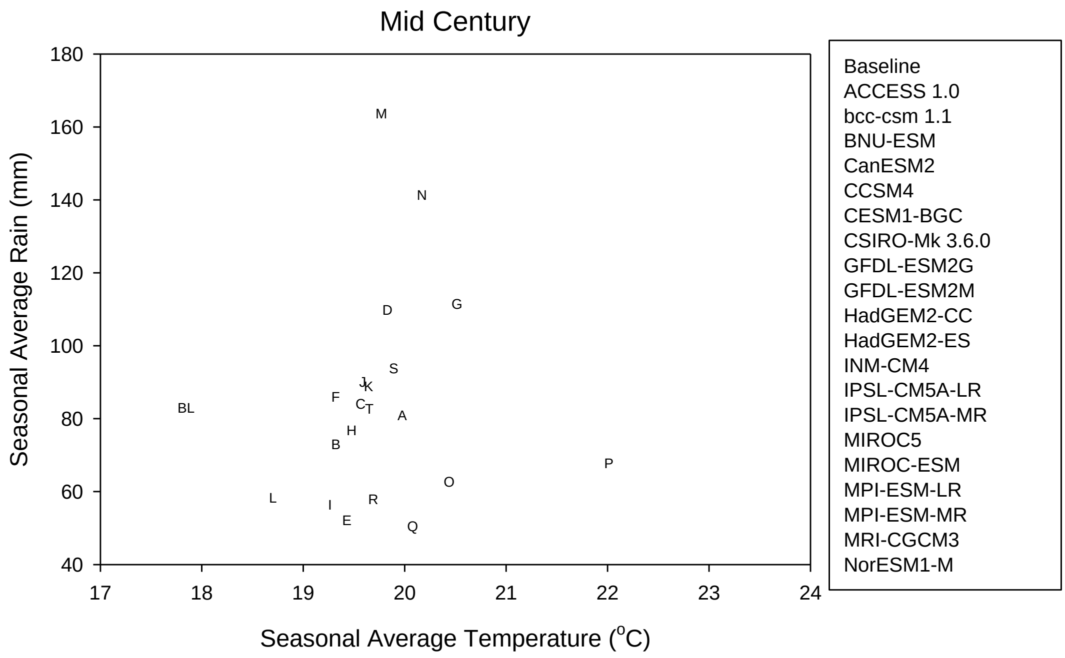


Fig 4.9: Seasonal (November to April) average temperature and rainfall generated by 20 GCMs for RCP 4.5 for Mid Century (2040-2069) and End of Century (2070-2099).

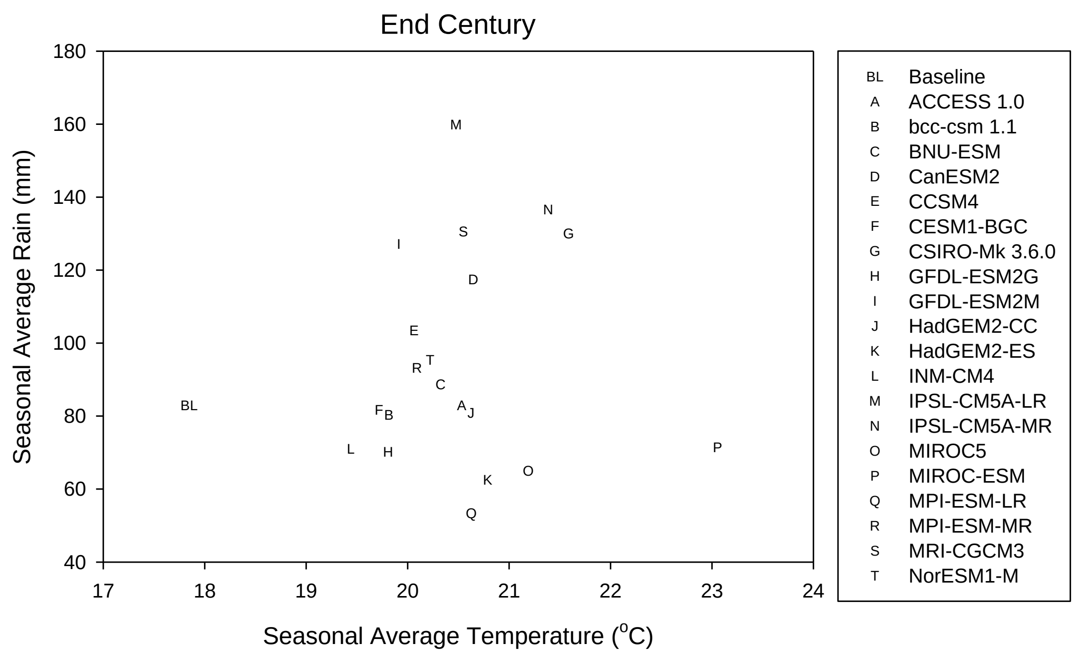


Fig 4.10: Seasonal (November to April) average temperature and rainfall generated by 20 GCMs for RCP 4.5 for Mid Century (2040-2069) and End of Century (2070-2099).

4.17 CLIMATE CHANGE IMPACT ASSESSMENT

4.17.1 Grain Yield:

Fig 4.10 shows that all the GCMs show reduction in grain yield for mid-century and higher reduction in grain yield for end of century. But the extent of decrease in yield varies with the GCMs. GFDL-ESM2M shows minimum reduction in yield while MIROC5 is a harsh GCM reducing the maximum grain yield for mid-century. All the GCMs show similar trend but higher extent of reduction in grain yield for end of century.

Comparing the GCMs with baseline, Wheat yield might decrease from 8.45% (GFDL-ESM2M) to 14.55% (MIROC5) in mid-century (Fig 4.11). In end century, wheat productivity might decrease by 19.03% (GFDL-ESM2M) to 22.55% (MIROC5). Although HadGEM2-ES had higher rainfall as compared to baseline, but the harmful effect of increased temperature is not compensated by rainfall. GFDL-ESM2M has minimum reduction in grain yield because according to this GCM, rise in seasonal average temperature is minimum. On the other hand, MIROC5 has translated its more increase in seasonal average temperature into maximum reduction in wheat productivity in both mid and end century.

This reduction in grain yield is primarily due to shortening of growing season length from 3 days (GFDL-ESM2M) to 7 days (MIROC5) in mid-century and 4 days (GFDL-ESM2M) to 9 days (MIROC5) in end century. Shorter growing season length has resulted in less interception of PAR and ultimately its low transformation into dry matter (Fig 4.12).

Gouache *et al.* (2012) found that heat stress during grain formation will increase, resulting in decrease in grain yield in wheat in near future. Stastna *et al*. (2002) evaluated CERES-Wheat Model at three sites and found good coefficient of determination ranging from 0.64 to 0.86. Ashfaq *et al.* (2012) reported increase in mean average temperature during vegetative stage would reduce wheat productivity by speeding up vegetative growth and reducing grain formation phase. Asseng *et al.* (2013) documented the variability in simulating the impact of climate change on wheat productivity. Rise in temperature varied depending on the GCM and its impact on grain yield also varied depending on the growth model used. However, all models predicted the decrease in wheat yield in future due to rise in temperature.

4.17.2 Total Dry Matter:

Seasonal analysis of effect of generated future weather data by using GCMs showed that all GCMs have significant impact in total biomass reduction (Fig 4.10). GFDL-ESM2M shows reduction in total dry matter but it was minimum as compared to baseline while MIROC5 has resulted in maximum reduction in TDM in mid-century. Same trend of GCMs was observed in end of century but TDM production is much lower as compared to mid-century due to increased seasonal average temperature.

As compared to baseline, GFDL-ESM2M shows a minimum reduction of 8.70% in total dry matter but it increased upto 12.69% if weather conditions are similar to MIROC5 in mid-century. For end of century, total dry matter of wheat crop could be reduced from 14.90% (GFDL-ESM2M) to 19.30% (MIROC5) compared to baseline. This reduction in total dry matter is also a cause for low yield of wheat (Fig: 4.11).

Roberts and Summer-field, (2007) reported that higher growth rate and earliness of anthesis is initiated by rise in temperature during the growth season which results in reduction in total dry matter accumulation. Koocheki and Nasiri (2008) also reported decrease in growth period in climate change study.

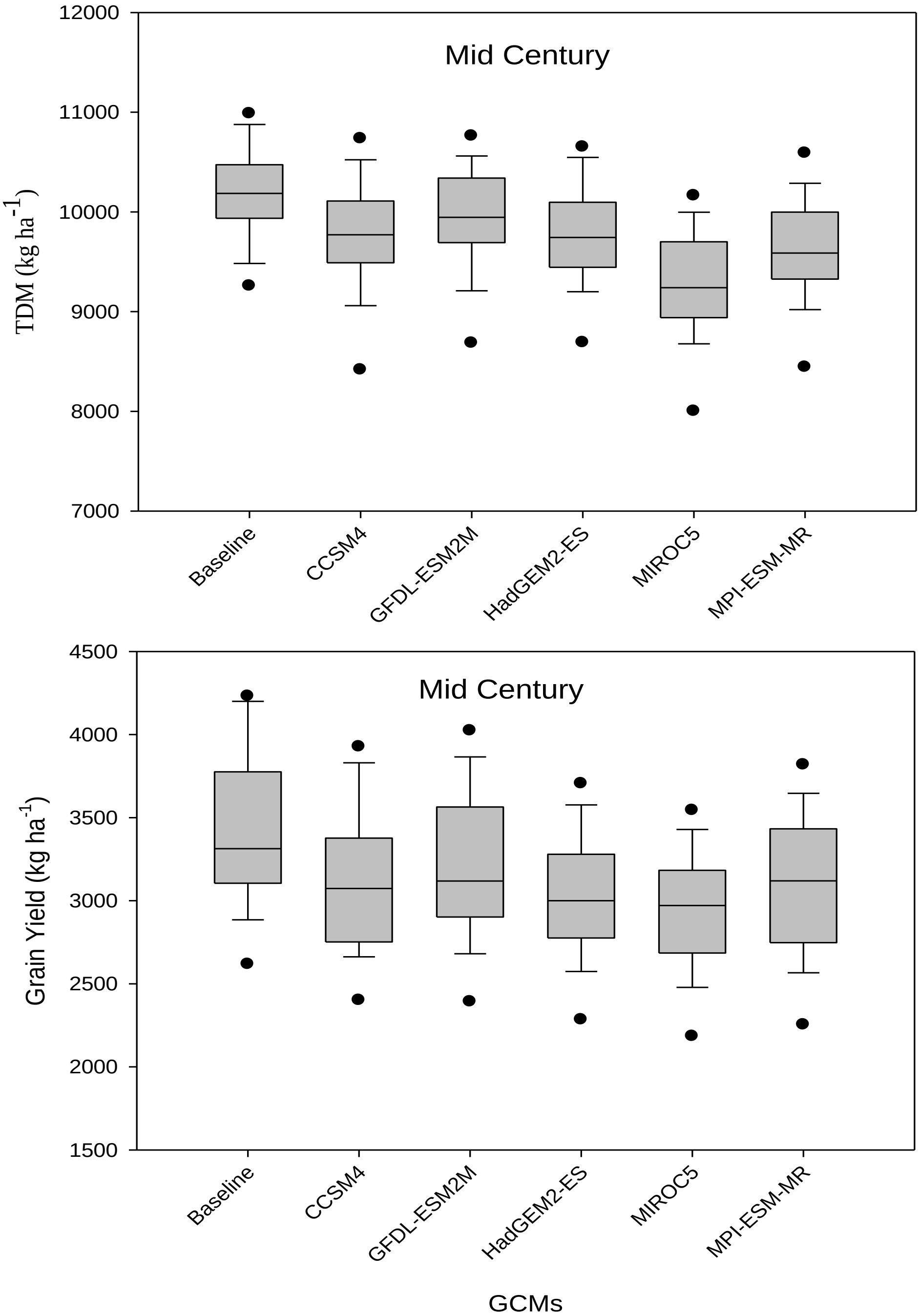


Fig 4.11: Seasonal analysis of climate change impact on wheat yield and TDM for mid-century presented in Box Plot showing 25, 50, 75 and 100 percentile.

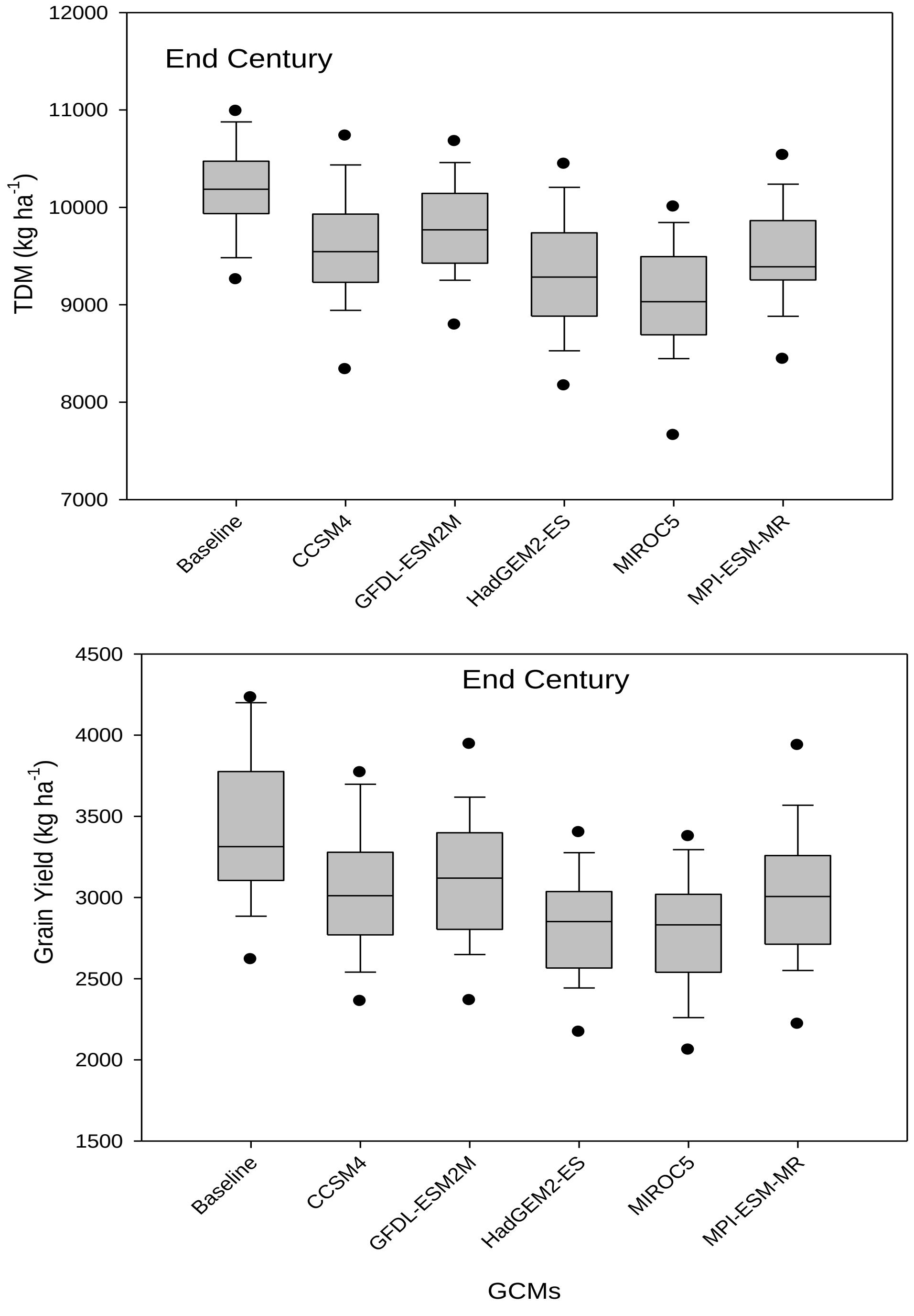


Fig 4.12: Seasonal analysis of climate change impact on wheat yield and TDM for end-century presented in Box Plot showing 25, 50, 75 and 100 percentile.

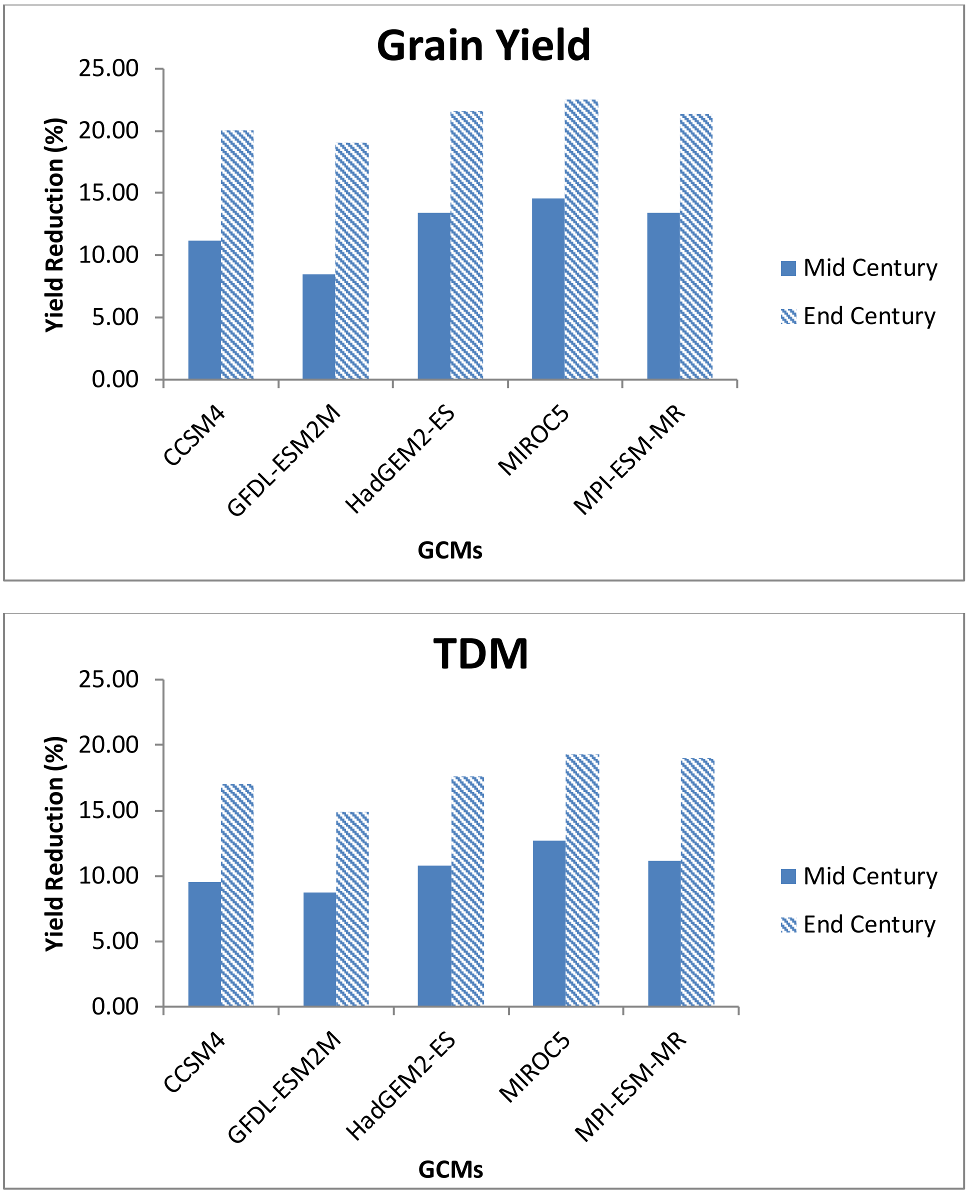


Fig 4.13: Percent reduction in Grain yield and TDM in Mid (2040-2069) and End Century (2070-2099) due to climate change by using weather data generated by five GCMs.

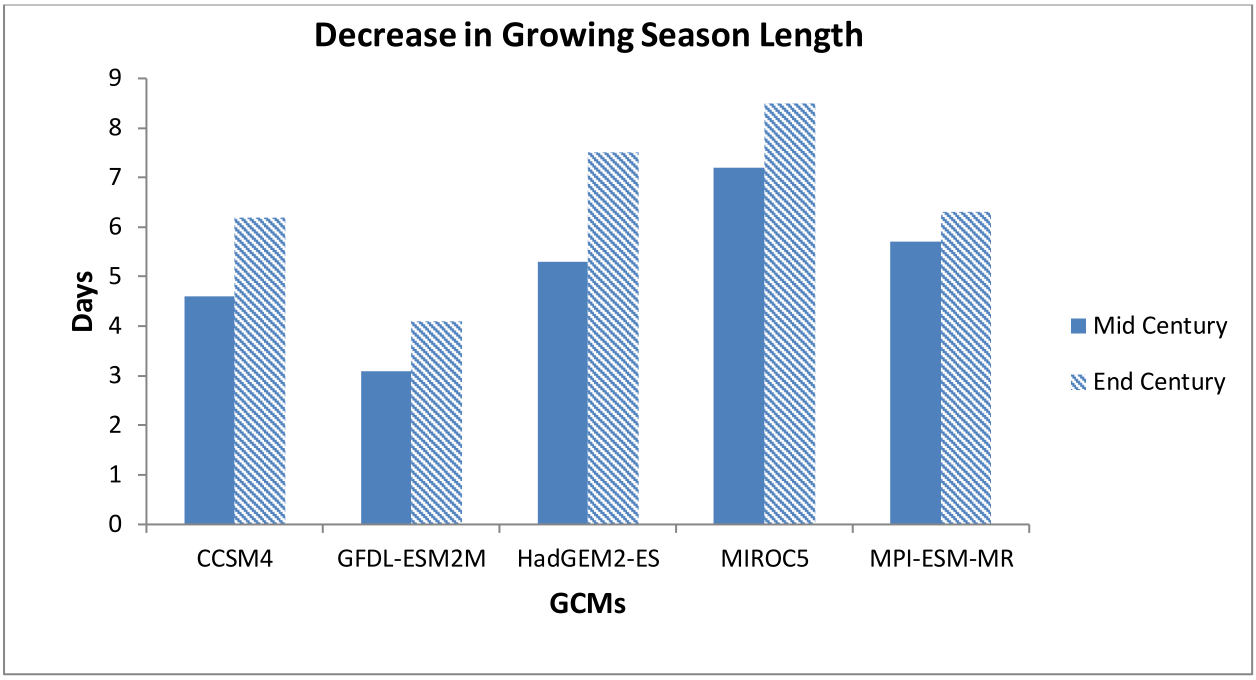


Fig 4.14: Decrease in growing season length due to rise in temperature as determined by different GCMs

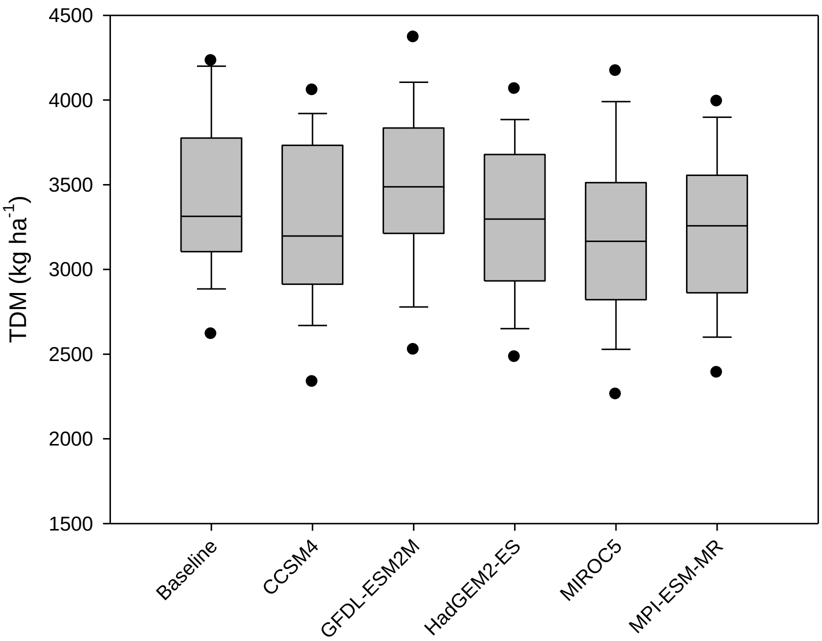


Fig 4.15: Hazardous effect of climate change reduced by applying package of adaptation strategies for five GCMs for Mid-Century (2040-2069).

4.18 ADAPTATION STRATEGY:

Representative agricultural pathways (RAPs) suggested by galaxy of scientists include re-defining sowing date, increasing fertilizer rate and plant density can be the possible options to reduce the harmful effects of climate change on wheat productivity. Scenario of less availability (twenty percent) was also considered as a problem protracting grain yield. Normally crop is irrigated with 300 mm water. If its quantity is reduced by 20% (60 mm), 240 mm water will be applied to the crop during the whole growing season. This hazardous effect of climate change and water shortage (by 20%) can be compensated by designing some adaptation strategies.

Model was run with strategy analysis of different sowing dates i.e. one week, two week and four week early as well as late sowing date as compared to recommended sowing date (15th November) by using five GCMs for mid-century (2040-2069). It was found that one week delay in sowing (22 November) performed best as compared to all other sowing dates in scenarios of mid-century. One week delay in sowing coupled with 20% increase in planting density could compensate the harmful effects of climate change and reduced water availability in mid-century (Fig 4.13). After applying the package of adaptation strategy, Median and 100th percentile of GFDL-ESM2M were even higher for mid-century (2040-2069) than baseline (1980-2009). Maximum harsh effects of climate change as described by MIROC5 could also compensate upto a large extent for mid-century.

Howden *et al.* (2007) highlighted the urgency of the focus on the adapting agriculture in future climate change. Shah *et al.* (2011) suggested some strategies to reduce the hazards of climate change. Replacement of sensitive cultivar with tolerant cultivar and avoid peak stress period by adjusting management options. Gouache *et al.* (2012) explored different management options like redefining sowing date, selection of earlier cultivars and increasing heat stress tolerance.

Chapter 5 SUMMARY

Field trials were conducted at Agronomy Research Area, Department of Agronomy, University of Agriculture, Faisalabad during Rabi season of 2010-11 and 2011-12. The objective of the study were to i) explore PSMD as an alternative approach for irrigation scheduling, ii) test the performance of CERES-Wheat model in simulating growth, development and yield of wheat under different planting dates, fertilizer levels and irrigation scheduling and iii) predict the effect of climate change on wheat productivity using CERES-Wheat model. Findings of my research are summarized below:

Experiment-I

- Full irrigation improved plant height, spikelets per spike, grain per spike, thousand grain weight, productive tiller and grain yield while deficit irrigation at different stages decreased the yield and yield contributing factors. Yield components and final grain yield was increased with increase in nitrogen rate from 80 to 120 kg ha^{-1} and higher nitrogen level (160 kg ha^{-1}) beyond 120 kg ha^{-1} did not show any significant increase in grain yield.
- LAI, LAD, TDM and CGR were minimum in irrigation at stem elongation and booting and full irrigation has improved all these growth traits. Increasing nitrogen rate from 80 to 160 kg ha^{-1} has significantly increased the value of growth parameter.
- Cumulative intercepted PAR and RUE for grain yield and TDM was maximum in full irrigation and deficit irrigation at different stages has decreased these parameters. Increasing fertilizer rates from 120 to 160 kg ha^{-1} did not have any significant effect on cumulative intercepted PAR and RUE for grain yield in 2010-11 while low fertilizer (80 kg ha^{-1}) rate decreased these parameters. RUE for grain yield in 2011-12 and RUE for TDM in both growing season was not affected by nitrogen rate.
- In 2010-11, full irrigation and three irrigations at different stages had statistically same WUE and two irrigations at different growth stages decreased WUE. In 2011-12, maximum WUE was recorded in full irrigation and it decreased as water was withheld at different stages. Nitrogen application at 120 and 160 kg ha^{-1} showed statistical WUE and it decreased with the decrease in nitrogen rate.

- Grain yield in 2011-12 was higher due to difference in weather conditions favoring high yield contributing factor.
- Economic analysis showed that net return and benefit cost ratio was maximum in full irrigation and 160 kg nitrogen ha^{-1}. It reduced to its minimum value in irrigation at stem elongation and booting and 80 kg nitrogen ha^{-1}.

Experiment-II

- 75 mm PSMD (Potential Soil Moisture Deficit) significantly reduced agronomic and yield related traits like plant height, spikelets per spike, grains per spike, productive tillers, thousand grain weight, grain yield and harvest index. Full irrigation and irrigation at 45 mm PSMD enhanced all these traits. Similarly all these characters attained maximum value with 15th November sowing as compared to 15th December sowing date.
- Leaf area index, total dry matter accumulation, leaf area duration and crop growth rate in full irrigation were statistically similar to irrigation at 45 mm PSMD while increase in deficit level has decreased these growth parameters. All these growth traits were decreased as sowing was delayed from 15th November to 15th December.
- High yield in full irrigation and irrigation at 45 mm PSMD is attributed to higher rate of grain growth and deficit irrigation has decreased rate of biomass accumulation in grain. Higher grain weight in 15th November sowing was attained by high rate of grain growth while delay in sowing upto 15th December resulted in low grain growth rate.
- Radiation interception and efficiency of conversion of PAR into grain yield and biomass was high in full irrigation and irrigation at 45mm PSMD. Increasing deficit level to 75 mm PSMD decreased these traits to minimum value. Total available PAR, cumulative intercepted PAR, RUE for grain yield and TDM was higher in 15th November sowing date and these were decreased significantly as sowing was delayed to 15th December.
- Grain yield production per unit of crop ET was higher in full irrigation and irrigation at 45mm PSMD and it decreased significantly with the increase in deficit level. Water use efficiency was higher in 15th November sowing date as compared to 15th December sowing date.

- Grain yield was higher in 2011-12 due to difference in weather condition supporting higher leaf area index, leaf area duration, cumulative interception of PAR and productive tillers as compared to 2010-11.

Crop growth modeling

- Model accurately simulated the phenology, yield and TDM for calibration treatment with error ranging from 0 to 1.75 %
- During evaluation, model simulated grain yield and TDM with R^2 0.72 and 0.90 and RMSE 446 kg ha^{-1} and 687 kg ha^{-1} respectively.
- Model was validated with data of 2010-11 having value of coefficient of determination (0.80 and 0.88) and low value of RMSE (359 kg ha^{-1} and 787 kg ha^{-1}) for grain yield and TDM respectively.
- Model made accurate simulation during evaluation and validation with second experiment showing that RMSE ranged from 272 to 412 kg ha^{-1} for grain yield and 945 to 1099 kg ha^{-1} for TDM.
- Climate change scenarios generated in R showed that there is rise in temperature in mid-century and rise in temperature in end century and variation in rainfall. The extent of rise in temperature depends on the GCM used.
- Grain yield is expected to decrease from 8.45 to 14.55% in mid-century and 19.03 to 22.55% in end century due to decrease in growing season length from 3 to 7 days in mid-century and 4 to 9 days in end century.
- Decrease in TDM is expected to range from 8.70 to 12.69% in mid-century and 14.90 to 19.30% in end century.
- Decrease in grain yield due to climate change and water shortage (by 20%) could be compensated by using a package of production technology (Delay in sowing by one week coupled with 20% increase in plant density) as suggested in RAPs (Representative Agricultural Pathway) for mid-century.

Conclusion.

- Full irrigation produced maximum grain yield due to higher value of its contributing components. Fertilizer level beyond 120 kg ha^{-1} did not show any statistically significant increase in grain yield. However net profit and benefit cost ratio is maximum in 160 kg N ha^{-1}.

- Deficit level of 45 mm PSMD can be used as an alternative to conventional farmer practice without any significant reduction in grain yield.
- CERES-Wheat model simulated phenology, growth and yield with a good accuracy during model calibration, evaluation and validation.
- Climate change scenarios for different GCMs show rise in temperature and variability in rainfall in mid and end century reducing grain yield by 8.45 to 14.55% and 19.03 to 22.55% and TDM by 8.70 to 12.69% 14.90 to 19.30% due to decrease in growing season length by 3 to 7 days and 4 to 9 days in mid and end century respectively.
- Adaptation strategy included change in sowing date from 15th to 22nd November and increasing seed rate by 20% to reduce the harmful effects of climate change and water shortage by 20% in mid century.

Future research

- Use of other crop nutrients like P and K in simulation study.
- Study genetic coefficient of cultivar to create heat tolerance.
- Use of different crop growth models to simulate variability in yield due to climate change.

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